The Influence of Minimal Footwear on the Biomechanics of Walking

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Rory Patrick Curtis

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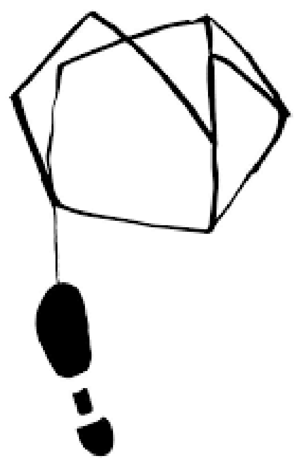

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Abstract

The purpose of this research project is to firstly investigate differences between barefoot, minimally shod, and conventionally shod walking. To secondly investigate the long-term effects of walking in minimal footwear on gait characteristics and foot function for healthy adults to better understand the biomechanical influence of footwear used in daily life.

This research investigates the foot function and gait performance of habitually conventionally western shod participants walking barefoot, minimally shod, and conventionally shod, before and after six months of transitioning to predominantly minimally shod walking (minimal footwear adaption or MFA group). This research also investigates indigenously minimally shod participants (indigenous footwear group), and experienced minimally shod (EMS) participants (2.5 ± 2.4 yrs experience) from a habitually conventionally western shod background.

The MFA participants had plantar pressure measurements, kinematics and kinetics evaluated while walking barefoot, minimally shod and conventionally shod pre and post a six-month intervention period requiring the participants to regularly wear minimal footwear in place of their conventional footwear. The MFA group also had foot strength evaluated pre and post invention period. The indigenous footwear group and EMS groups had plantar pressures and foot strength evaluated.

Plantar pressure distributions were not significant different between barefoot, minimally shod, and conventionally shod walking within all the groups. However, MFA centre of pressure trajectories along with the kinematic and kinetic pre-intervention period results revealed minimally shod walking to be an intermediate between barefoot and conventionally shod walking. MFA post-intervention period results showed small changes to minimally shod walking gait characteristics that had an overall trend to converge to barefoot gait characteristics. However, these changes were slight and minimally shod walking still remained a unique intermediate between the other two walking conditions. The EMS dynamic centre of pressures showed that minimally shod walking was still distinct from barefoot walking confirming that experience in minimally shod walking has a limited effect on gait characteristics. MFA foot strength increased by 57.4% after regally walking in minimal footwear for six months. Both the EMS and the indigenous footwear groups had comparable foot strengths to the post intervention period MFA group suggesting six months of minimal footwear use is sufficient to achieve natural level foot strength.

This study shows that minimally shod walking is an intermediate between barefoot and conventionally shod walking for healthy adults and experience in minimally shod walking has a limited influence on these gait characteristics, however foot strength will increase substantially.

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List of abbreviations

CoP	Centre of pressure
EMS	Experienced Minimally Shod
FFF	Future Footwear Foundation
HBM	Habitually barefoot and/or minimally shod
MFA	Minimal footwear Adaption
MPJ	Metatarsophalangeal joint
MPJ.STAR	Metatarsophalangeal joint strength tester and recorder
pSPM	Pedobarographic statistical parametric mapping
TFS	Toe Flexion Strength

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To my Mum and Dad

1. Chapter 1: Introduction

1.1. Purpose of research

Footwear plays a large role in daily life. Its frequency of use and role as a buffer between the ground and the foot means it has potential to influence the user's biomechanics in everyday life. Many studies focus on the footwear's influence on biomechanics relating to sporting performance, whereas fewer studies have investigated the influence of footwear on walking biomechanics. Walking biomechanics studies, tend to focus on individuals with musculoskeletal pathologies, impairments and/or disabilities. Studies that investigate the influence of footwear on walking biomechanics on the healthy majority are more limited. With this current limited knowledge, the general public prioritise fashion over function when selecting footwear for daily life, unaware of how their choice may affect their health. It is therefore important to build up this literature and challenge the current assumptions associated with conventional footwear design.

The Future Footwear Foundation (FFF) at KASK, School of Arts, Gent, has been set up to bring footwear into the future. The foundation combines design, anthropology, and biomechanics to create footwear that is sustainable for the body and the environment. One aspect of FFF is to tackle misconceptions with footwear and its impact on health. The purpose of this research project is to add to this knowledge and investigate the influence of footwear on the biomechanics of walking.

1.2. Human Body

To understand the influence footwear has on biomechanics, an understanding of gait characteristics and the human musculoskeletal structure associated with gait is essential.

1.2.1. Bipedal locomotion

The anatomy underlying the gait of anatomically modern *Homo sapiens* is highly specialised to bipedal locomotion. All hominins (modern humans and their earlier relatives) showed signs of bipedalism Thorpe et al. (2007) and as hominin evolution progressed, many hominin ancestors predominately walked upright, by around six million years ago (Brunet et al., 2002, Senut et al., 2001). Finally, anatomically modern *Homo sapiens* (present from around 200,000 years ago (McDougall et al., 2005)) walked with efficient habitual bipedalism. Several specialised anatomical adaptions developed during hominin evolution that led to this efficient bipedal locomotion of anatomically modern *Homo sapiens*. Many of these adaptions occurred in the foot.

1.2.2. Anatomy of the Foot

The human foot is astonishingly complex and highly specialised. It is composed of 26 bones, 33 joints and 19 muscles (Marieb and Hoehn, 2007). It took millions of years of evolution for the human foot to become so specialised. *Homo sapiens* feet evolved from one similar to the feet of current African Apes. These feet went from a flexible hand-like appendage, suited to a mix of terrestrial and arboreal locomotion (Crompton et al., 2008), to a stiffer and more robust, spring-like lever appendage, to excel in predominately terrestrial locomotion. In order to achieve these variations; the hallux became enlarged and adducted, all the other toes reduced in size, and the tarsal bones rearranged to become more compact and the medio-lateral arch formed (McKeon et al., 2015).

The medial longitudinal arch is very prominent in modern day *Homo sapiens.* The arch is made up of the calcaneus, the bones of the midfoot and the metatarsals, along with the many ligament attachments connecting these bones together. The arch is supported by the plantar aponeurosis. The plantar aponeurosis is a fascia running from the tuberosity of the calcaneus to the metatarsal heads. Early studies have shown that the longitudinal arch gains much of its spring like function through the plantar aponeurosis (Ker et al., 1987). The spring like function of the longitudinal arch as well as the Achilles tendon increases the efficiency of locomotion due to their elastic energy storing capabilities (Alexander, 1984). Recently it has been proven that the energy cost of locomotion is indeed directly reduced by the plantar aponeurosis (Stearne et al., 2016). It is thought to improve running efficiency by returning 8 – 17% of the mechanical energy required through passive mechanisms alone (Ker et al., 1987, Stearne et al., 2016, Hicks, 1954).

Homo sapiens also have considerable intrinsic foot musculature. These muscles allow *Homo sapiens* to control balance while in single leg support. The deformation of the medio-lateral arch of the foot is controlled by the intrinsic and extrinsic muscles of the foot and it is these muscles that give the foot its core strength and ability to assist with balance (McKeon et al., 2015).

The foot is connected to the rest of the lower limb via the ankle joint (otherwise known as the talocrural joint). It is a synovial joint between the tibia and fibula of the shank and the talus of the foot. On its own the joint permits plantarflexion and dorsiflexion of the foot. The ankle joint is also part of the ankle joint complex which includes the subtalar joints as well (the talocalcaneal and talocalcaneonavicular joints), and the combination of these joints allows for three-dimensional motion through the transverse, sagittal and frontal anatomical planes (Lundberg et al., 1989, Siegler et al., 1988). The ankle joint complex allows for a large range of motion in both plantarflexion/dorsiflexion and inversion/eversion. Pronation is a complex motion that involves the combination of dorsiflexion, eversion, and external rotation, whereas supination is the combination of plantarflexion, inversion and internal rotation (Willems et al., 2017).

1.2.3. Gait

Gait is simply the term used to describe an animal's manner of locomotion. For humans, gait is typically used to describe the variations in locomotion characteristics during running and walking. The time from one foot contacting the ground until the other is a step, and two steps make a gait cycle. In both running and walking, stance phase and a swing phase make up the gait cycle. The stance phase defines the time a foot is in contact with the ground. During this time, the body is supported by this foot and the leg it belongs to. The swing phase defines the time a foot is airborne. The stance and swing phase can be broken down into further sub-phases. The stance phase is made up of the initial contact, loading response, mid-stance, terminal phase and pre-swing; and the swing phase is made up of initial swing, mid-swing and terminal swing (Perry and Davids, 1992). The gait cycle and its further sub-divisions are illustrated for a walking gait in Figure 1.1, below:

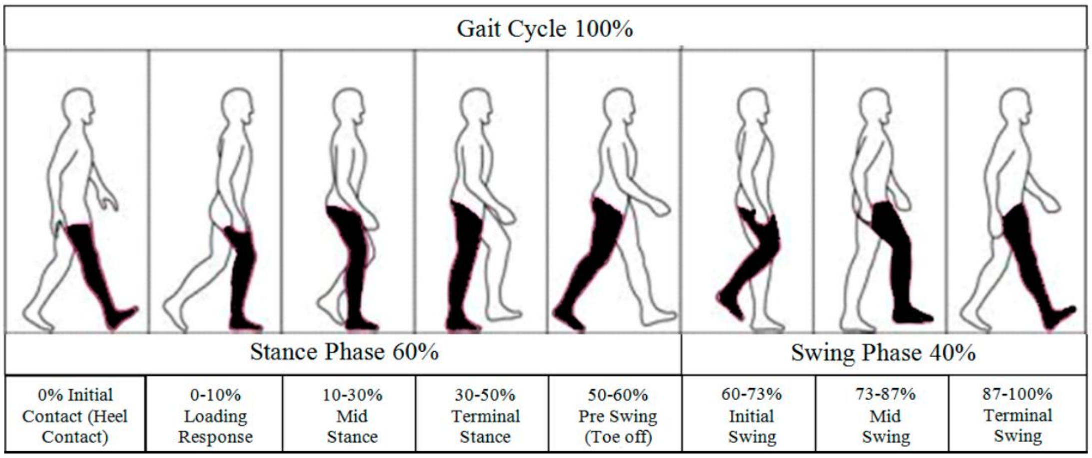

Figure 1.1: Chart illustrating a typical healthy adult walking gait. Adapted from Anwary et al. (2018).

Figure 1.1 shows that stance phase and swing phase for typical walking are roughly 60% and 40% of the gait cycle respectively, and the sub-phases take a given percentage of the gait cycle as well. It provides a good standard but should be only used as a rough guide as gait cycle timing is dependent on walking velocity (Liu et al., 2014). The ratio between the stance phase and the gait cycle is defined as the duty factor. Faster locomotion will have a smaller duty factor as the stance phase will decrease. The reason duty factor changes with velocity is due to efficiency. It is more efficient to run for any duty factor less than 0.5, and walk for any duty factor more than 0.5 (Alexander, 1991).

Step length and step frequency change as a result of walking speed in order to reduce the energy cost associated to the locomotion (Bertram and Ruina, 2001, Kuo, 2001, Kuo et al., 2005), along with step width (Maxwell Donelan et al., 2001).

Walking is a highly efficient form of locomotion. Its efficient characteristics were first described by the inverted pendulum model (Alexander, 1976, Mochon and McMahon, 1980). Named as such, due the inverted pendulum motion the centre of mass of the body takes while being pivoted about the stance foot. Figure 1.2 shows the workings of the inverted pendulum walking model.

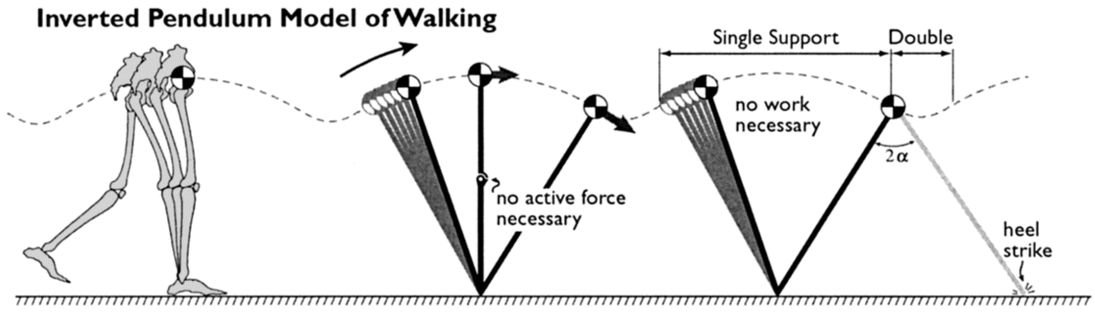

Figure 1.2: Schematic illustrating the inverted pendulum model of walking. Adapted from work by Kuo et al. (2005).

Figure 1.2 shows the trajectory of the centre of mass and the inverted pendulum motion as it is pivoted about the stance foot. At mid-stance the body's centre of mass is at its highest point during the gait cycle, and it is at this point the inverted pendulum motion comes into effect. From terminal stance to pre-swing the body's centre of mass rotates about the stance foot, converting potential energy into kinetic energy. The kinetic energy gained will then mostly convert back to potential energy from the heel strike of the swing leg to its progression to mid-stance, saving energy via the conservation of the body's mechanical energy. This process repeats itself until walking is stopped or interrupted. The inverted pendulum is a theoretical model that is 100% efficient. Walking in the real world is only around 70% efficient, but the inverted pendulum model offers the first insight into walking kinematics.

The idea of the pendulum models has been around ever since Borelli likened walking to vaulting over a stiff leg, whilst using an architect's compass to demonstrate (Borelli). For many years it proved as a sufficient model however, as is often the way of science, new and improved methods and analytical processes have revealed the inverted pendulum model to be an overly simplified model for walking. The inverted pendulum model assumes a stiff stance leg to vault over, and this has been shown to not accurately represent walking (Full and Koditschek, 1999). Numerous studies have shown the leg's ability for altering its stiffness (Ferris et al., 1998, Ferris and Farley, 1997, Farley et al., 1998). It has also been shown that a compliant stance leg is required for basic walking (Geyer et al., 2006), similar to the spring-mass model (McMahon and Cheng, 1990) or the spring-loaded inverted pendulum model (Schwind, 1999) used to describe running. A model that takes into account leg compliance when walking can be seen in Figure 1.3, below:

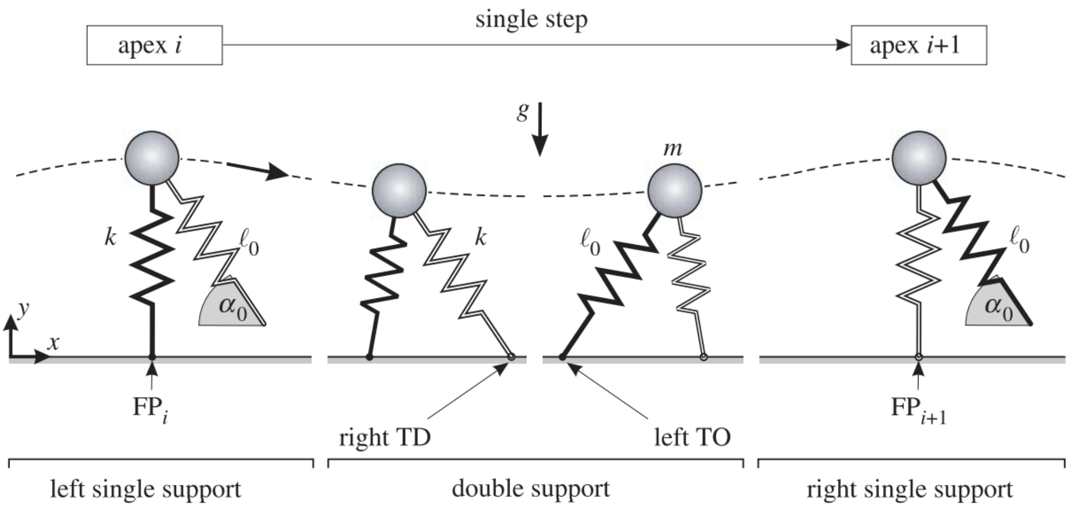

Figure 1.3: Inverted pendulum walking model with a simple spring and mass to represent leg compliance and the centre of mass of the body respectively (Geyer et al., 2006).

Results taken from the model shown in Figure 1.3, show that walking is a bouncing gait much like a running gait (Geyer et al., 2006). This model causes both positive and negative work during the stance phase. Figure 1.4 illustrates where negative work is performed. It is these incidents of negative work that largely contribute to walking not being 100% efficient.

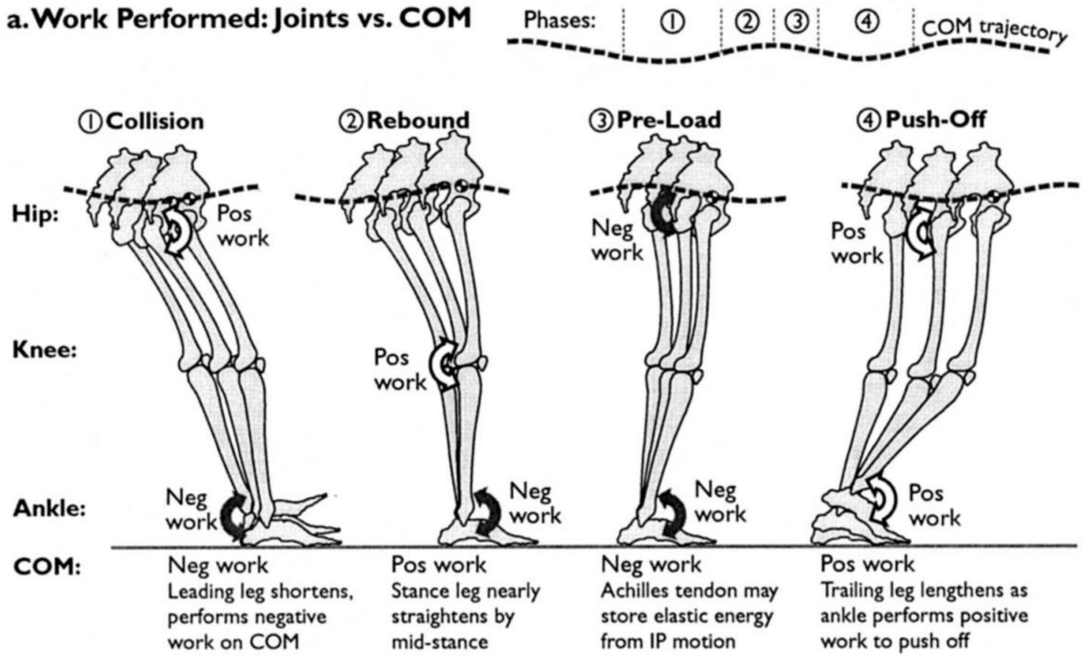

Figure 1.4: Diagram detailing the theorised internal energy costs during stance phase for a compliant leg walking model (Kuo et al., 2005).

The human body can be considered as a dynamic mechanical system. In theory, the human body can be fully represented by a mass – spring – damper system with active feedback. The spring – mass – damper system defines any given size of body segment by its mass, elastic and viscoelastic properties, and defining its relationship to its neighbouring body segments. The active feedback in the body is the neuro-muscular control triggered by both internal and external sensation. The spring – mass – damper system is the passive part of the system and the neuro-muscular control is the active part. Both the passive and active parts of the system are required for effective locomotion.

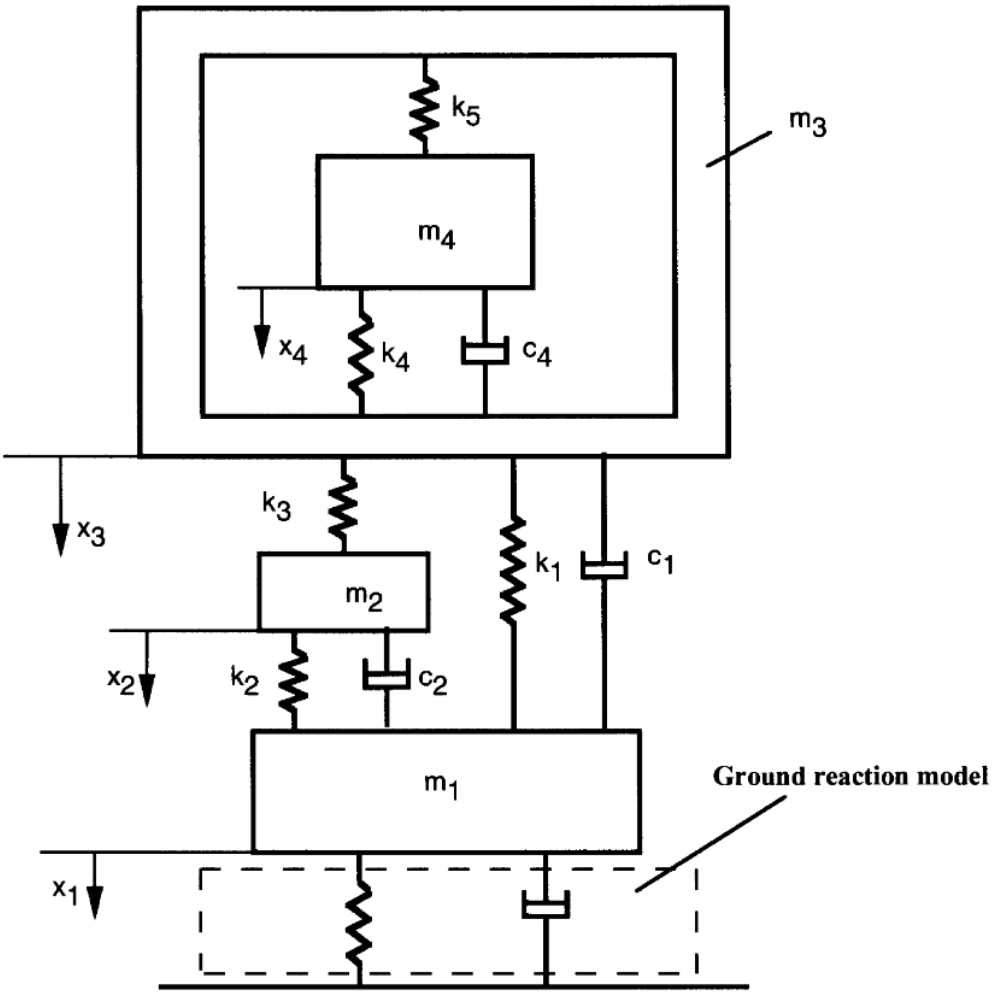

Figure 1.5: Simple passive mass – spring – damper system of the human body, taken from Nigg et al. (Liu and Nigg, 2000). The elements shown in the system are the lower body (those with 1 and 2 subscript, for the rigid and wobbling elements of the lower limb, respectively), and upper body (those with 3 and 4 subscript, for the rigid and wobbling elements of the lower limb, respectively).

The most useful walking simplified model is the spring mass inverted pendulum model (Geyer et al., 2006), as it considers compliant legs. Therefore, efficient walking is affected by two main factors; the conservation of momentum of gait direction, and the efficiency the lower limbs ability to absorb, store and return the energy on impact.

"Walking and running ultimately boils down to the mechanical challenges of generating an impulse by means of the interaction between feet and the ground"(Willems et al., 2017). During the stance phase, the stance foot impacts the ground and due to Newton's 3rd law of motion, an equal and opposite force acts on the locomotor. This force is known as the ground reaction force. The force is three dimensional, and is made up of vertical, medial-lateral, and anterior-posterior components. This can be seen in Figure 1.6.

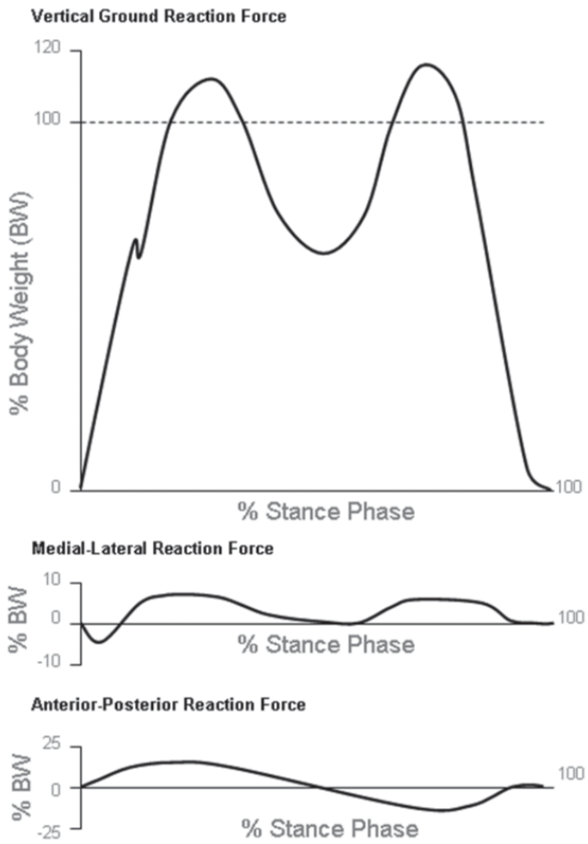

Figure 1.6: Components of ground reaction force for typical healthy walking (Berke et al., 2008).

The sum of vertical ground reaction forces from the entire stance phase (impulse) will equate to body mass. There is often a vertical ground reaction force peak during initial contact. It is more noticeable in a running gait, but the peak can be present for walking as well, as can be seen in Figure 1.6. The magnitude, loading rate and way the foot strikes the ground at initial contact is believed to influence injury potential during running (Clement et al., 1981, Hintermann and Nigg, 1998, James et al., 1978, Nigg, 2001). It is currently unknown if the initial contact vertical ground reaction force influences injury potential during walking.

In conclusion, a healthy walking gait will: efficiently conserve the momentum of gait direction, efficiently absorb, store and return the energy, minimise vertical ground reaction force peaks, and finally, provide postural support preventing vertical collapse of the body during locomotion (Winter, 1995), and adapt to the locomotion substrate. The foot aids in all these criteria for a healthy walking gait.

1.2.4. Biomechanics of the Human Foot

The foot is the body's only contact point with the ground. Forces produced by the muscles and by acceleration of the centre of mass are transmitted to the ground via the foot to generate forward propulsion on top of supporting body weight (Wang and Crompton, 2004, Crompton et al., 2010). The foot transmits this propulsive force during the push-off phase at which point it acts as a relatively stiff and an effective lever, pivoting about the subtalar joint (Palastanga et al., 2006). In contrast, the foot is a compliant shock absorber during impact. The foot has multiple built in mechanisms which enables this stiffness variation ability. One of such mechanisms is known as the windlass mechanism. The windlass mechanism enables the foot to be an effective shock absorber on impact and an efficiently stiff force transmitter during push-off (Griffin et al., 2013). The windlass mechanism tightens and relaxes of the longitudinal arch via the plantar aponeurosis (Hicks, 1954). During initial contact, the longitudinal arch compresses and absorbs the mechanical energy from the ground reaction force. Some of this energy is stored as elastic energy in the plantar aponeurosis (Ker et al., 1987, Stearne et al., 2016, Erdemir et al., 2004). The stance phase continues through mid-stance to the terminal phase. At this point the toes are passively dorsiflexed about the metatarsophalangeal joint, stretching the plantar aponeurosis distally over the metatarsal heads. At the same time, the triceps have activated to generate the propulsive force required for push off. The activated muscles shorten and pull the Achilles tendon superiorly. This pulls the calcaneus back, which in turn tightens the plantar aponeurosis proximally. Therefore, the plantar aponeurosis has been tightened from both ends, which in turn stiffens the longitudinal arch providing the stiff foot required for efficient push off at the stance phase. Additionally, the elastic energy stored within the plantar aponeurosis is released at the end of the push off phase, thereby increasing locomotion efficiency. The plantar aponeurosis may act passively but it is also influenced by extrinsic foot muscles such as the triceps surae. As the triceps surae tension increases so does that of the plantar aponeurosis (Cheung et al., 2006).

It is not just the plantar aponeurosis that is responsible for the stiffness variation capabilities of the human foot. Studies have also shown that the intrinsic foot muscles actively influence longitudinal arch stiffness in addition to the passive tightening and relaxation of the plantar aponeurosis (Kelly et al., 2015, Kelly et al., 2014, Fiolkowski et al., 2003, Headlee et al., 2008, Mulligan and Cook, 2013). Two of these studies found that activation of the Abductor Hallucis, Flexor Digitorum Brevis and Quadratus Plantae resulted in the stiffening of the longitudinal arch (Kelly et al., 2014, Kelly et al., 2015). Neural feedback via sensory feedback from mechanoception and proprioception also regulate longitudinal arch stiffness during gait events, in addition to the passive and active mechanisms. Therefore, overall foot stiffness is governed by the interplay between passive, active and neural subsystems that is known as the foot core system (due to its similarities to the lumbopelvic-hip core) (McKeon et al., 2015). These systems are illustrated in Figure 1.7, below:

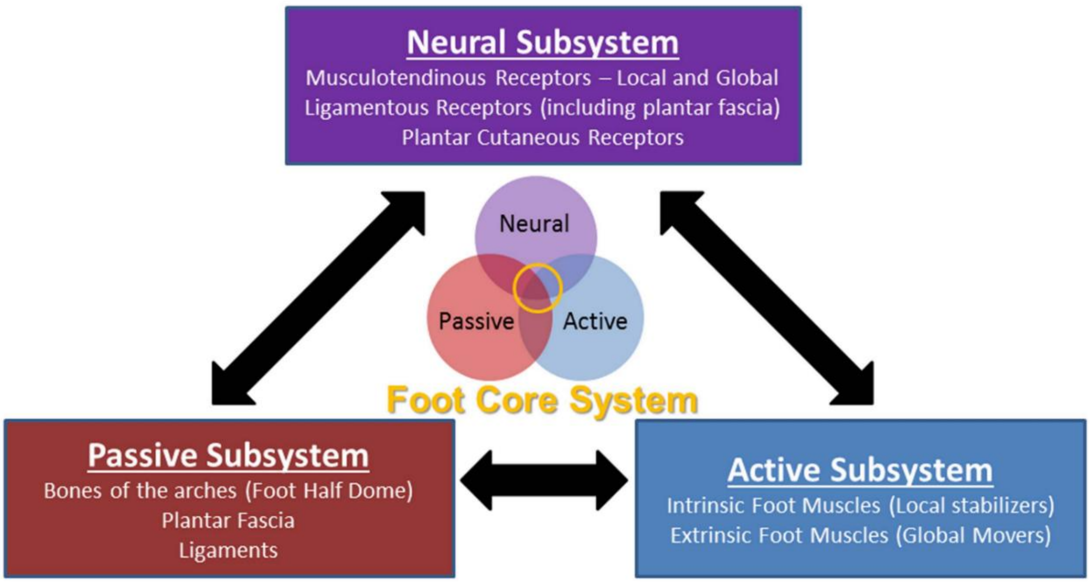

Figure 1.7: Figure illustrating the workings of the foot core system, the mechanism underlying foot stability (McKeon et al., 2015).

Figure 1.7 shows the interplay of the components of the foot's anatomy key for effective gait. The somesthetic system allows the receptors of the neural sub-system to engage with the active subsystem to control balance and movement (Kavounoudias et al., 2001). In addition to this there is a high concentration of fast adapting cutaneous mechanoreceptors found in the sole of the foot suggesting a high dynamic sensitivity (Kennedy and Inglis, 2002), which is highly important for balance, one of the key factors for gait (Winter, 1995). The fast-adapting receptors make up the majority of the mechanoreceptors in the foot and are key for sensation at initial contact and terminal phase through to pre-swing during walking (Perry et al., 2000).

Plantar sensation is a vital factor to gait and balance. Studies have shown that reduction in plantar sensation leads to gait abnormalities (Eils et al., 2002, Hoch et al., 2012, Kavounoudias et al., 1998, Kavounoudias et al., 2001, McKeon and Hertel, 2007, Alfuth and Rosenbaum, 2012). These gait abnormalities can impair balance control, increasing the risk of falling (Höhne et al., 2012, Perry et al., 2000, Meyer et al., 2004, Nurse and Nigg, 2001).

1.3. Barefoot Walking versus Shod Walking

Humans walked barefoot for most of our history and during that time the foot has evolved into a highly specialised tool for bipedal locomotion. For thousands of years our ancestors did not only survive without any footwear but thrived. It is therefore reasonable to assume that footwear is not required at all and barefoot walking could be best for both our musculoskeletal health and gait performance. However, there are two main issues with this assumption:

1) Evolution is a process that allows for survival of the fittest (e.g., best adapted to the environment), meaning that humans walking barefoot could have been just good enough for survival. Evolution is not a perfect optimisation process; therefore barefoot walking may not be "optimal". It is possible that the footwear we have invented could be a tool that improves upon what we already have.

2) Gait characteristics are influenced by the locomotion surface (Dixon et al., 2000). Hominin bipedal locomotion evolved to suit terrestrial locomotion over natural substrates; however, locomotion is typically performed over artificial substrates in the present day. This means that even if we assume barefoot walking was optimal for anatomically modern *Homo sapiens* on

natural substrates, it does not necessarily translate to artificial ones. This is because *Homo sapiens* have not had the time to adapt to the rapid change in the substrate's mechanical properties.

In addition to these points, it is important to note that some features of footwear are very useful. For example, they protect our feet from sharp objects and unhygienic surfaces and keep our feet warm. An argument could even be made in favour for cushioning in footwear, as a shock absorber on the unforgiving artificial substrates we are accustomed to. Considering this, the scope of this research will not only investigate barefoot walking but shod walking as well.

1.4. Footwear

The Oxford dictionary defines footwear as 'outer coverings for the feet, such as shoes, boots, and sandals' (Stevenson, 2010). There is no other definition that can be more concise as there are so many types of footwear design. It is hard to imagine a world without the plethora of footwear designs we have today, but footwear started from humble beginnings, and evolved into what it is today.

1.4.1. History of Footwear

The oldest footwear discovered has been carbon dated to 8300 years old (Kuttruff et al., 1998). The footwear was found in the Chevelon Canyons of the southern Colorado Plateau, Arizona, USA. It was a warp faced plain weave sandal made from a fibrous plant material. The sandal was very minimal and offered no foot support and was most likely used to protect the wearer's feet from the terrain. Other shoes of similar constructions have been found dating from 6900 – 3200 years ago (Geib, 1996, Kuttruff et al., 1998, Pinhasi et al., 2010). These shoes were either sandal or moccasin like, and had some leather incorporated into the design. Figure 1.8 shows what these shoes looked like.

Figure 1.8: Modified image from Kuttruff et al. (1998).

Footwear has been around for much longer than the direct records. Direct records are limited due to the perishable nature of the early footwear. Based on fossil records of changes in the lessor toes, footwear is believed to have existed from around 40,000 years ago (Trinkaus, 2005). The footwear was likely to be very similar to the direct records discovered – a minimal sandal/moccasin construction made from fibrous vegetation, and perhaps even leather.

Footwear remained very basic in construction through most of its history, with simple leather or plant fibre designs found in ancient Egyptian (Veldmeijer, 2009a, Veldmeijer, 2009b, Veldmeijer, 2009c) and Roman (Sesana, 2005) communities. In the 15th century heels were added to shoes, but to increase military advantage as opposed to aid with daily life. Persian soldiers would wear heeled shoes while riding on horses to anchor themselves in the stirrups and improve their stability for firing their bow and arrows (Semmelhack, 2017). From around this time however, fashion over function footwear started to emerge for the aristocracy as a way to convey their status over the "lesser" classes (Semmelhack, 2017). However, it wasn't until the latter end of the industrial revolution, in the 19th century that shoes with cushioned heels became readily available to the western population (Shawcross, 2014). In the last 50 years, complex support mechanisms have been incorporated into footwear design for running shoes (Shawcross, 2014, Lieberman et al., 2010, Shorten, 2000), with the invention of the contemporary running shoe in the 1970s (Cavanagh, 1980). Many of these design features have inspired the design of some types of daily footwear, adding to the diverse world of footwear types.

1.4.2. Footwear types and general anatomy

Footwear is extremely variable in our modern age. It can be broken down into a near infinite number of classifications. Despite this great level of variation in footwear, most footwear can be described with the same general footwear anatomy. This anatomy is lined out in Figure 1.9 below:

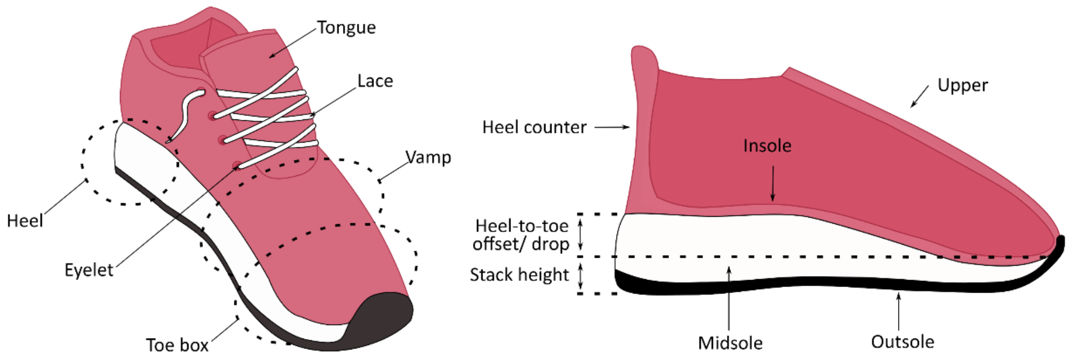

Figure 1.9: Typical footwear anatomy, based off a fashionable trainer design.

Figure 1.9 shows that footwear typically comprises of two main parts: an upper and a sole. The upper enclose the top half of the foot and the sole lays beneath the foot. The sole is often comprised of three parts: the insole, midsole, and outsole. The outsole is designed to be durable and is often constructed from materials such as rubber or leather. The insole is the foot's contact point with the sole, it is often designed to cradle the foot by following typical foot contours. The midsole is added to attenuate load during locomotion and is typically made of specially designed viscoelastic plastics. Often midsole thickness is greatest at the heel of the shoe to provide more support where impact forces are typically greatest during locomotion, creating a positive heel-to-toe offset. Other types of footwear that do not have a midsole present will still typically have a positive heel-to-toe offset simply by the raise the heel of the shoe.

The minimum thickness of the total sole is referred to as stack height. Stack height and heel-to-toe offset together make up the total heel height. Another important section of footwear is the toe box area. The toe box area is at the front of the shoe and envelopes the toes all the way down to the metatarsophalangeal joints. For the last few decades, a small toe box area has been considered fashionable and as a result footwear is typically made with a restrictive toe box area that compresses the toes.

There are of course footwear types that do not have restrictive toe box areas and there are some that do not follow some of the other features found in '*typical'* footwear. The great variety in footwear makes it hard to categorise footwear into a manageable number of categories for research that truthfully represents the footwear wearing habits of the public. For the purposes of this research all footwear is grouped into one of two categories, either 'conventional' or 'minimal' footwear. Minimal footwear is defined as 'Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices' (Sinclair et al., 2013) and, for the purposes of this research, an absence of a restrictive toe-box area. An example of minimal footwear can be seen in Figure 1.10. Conventional footwear is any footwear that falls outside this definition. These two distinct definitions of footwear include all types of footwear, and along with barefoot, make up the three walking conditions that will be investigated for this research. The walking conditions that will be investigated in this research are:

- Barefoot
- Minimally shod
- Conventionally shod

Figure 1.10: An example of minimal footwear: Vivobarefoot Stealth II images, images sourced from Vivobarefoot website (Vivobarefoot, 2017).

The definition of conventional footwear covers a large variety of different types of footwear. It encompasses every type of footwear from the Nike Vaporfly series with soles constructed of thick elastic foams and carbon fibre plates (that aided Eliud Kipchochage's sub two-hour marathon time), to the humble plimsoll, whose only feature preventing from falling into the minimal footwear definition is its restrictive toe box area and a slightly thicker sole. This range of footwear types will have high variations in key spatial and mechanical properties, that may cancel each other out when grouped together thereby making conventional footwear comparisons to minimal footwear less pronounced. Greater differences between minimal footwear and conventional footwear would be observed if the conventional footwear was controlled to one standard model. Differences in minimally shod and conventionally gait characteristics would also likely increase. However, this is not an actual portrayal of the use of conventional footwear in daily life. One aspect of conventional footwear is how variable it is during daily life. This thesis will study the full range of conventional footwear (as it is defined within this thesis) to capture the impact conventional footwear has on daily life. In addition to this, despite the large variety of footwear type this definition for conventional footwear includes, we are confident that significant mechanical and spatial differences exist between both conventional and minimal footwear that can influence gait characteristics and musculoskeletal health. This is because the current literature has already shown some of these differences (Franklin et al., 2015).

The spatial and mechanical differences of footwear that will be reviewed within this thesis are:

- Sole Thickness
- Upper thickness
- Sole offset
- Shoe length
- Shoe Width
- Shoe Weight
- Bending Stiffness
- Sole softness – the opposite of sole hardness, the standard measurement used in this used to characterise sole compression. Sole softness was used within this study due to methods limitations. More information is available within chapter three.

All the above measurements are explained in detail within chapter three.

1.4.3. Footwear Experience and General Literature on Footwear Biomechanics

The definition of conventional footwear used for this research only applies to the footwear typically worn by people from modern western cultures. People within these communities have typically worn conventional footwear (as defined in this research) their entire lives; they are habitually conventionally western shod, and '*conventional'* footwear is the convention to them. However, some people from other cultures have a very different relationship to footwear. There are indigenously minimally shod communities where minimal footwear would be their conventional footwear, and habitually barefoot communities where no footwear at all is the convention. For the purpose of this research, participants that come from modern western, indigenously minimally shod, and habitually barefoot communities will be referred to as habitually conventionally western shod, indigenously minimal shod, and habitually barefoot respectively when being compared to one another. Additionally, the definition of conventional footwear will only apply to the habitually conventionally western shod communities.

Barefoot locomotion is not common in contemporary (city) environments. It is often limited to the midnight amble from the bedroom to bathroom, and back again. However, communities that are habitually barefoot or at least barefoot for significant periods of time, still exist. They often live in remote and less economically developed areas of the world. Due to their remote nature, few studies have been conducted on these communities, and even fewer on their biomechanics.

In the 1940s, habitually barefoot communities were much more common. One study from the 1940s, conducted by an army physician surveyed the feet of such a group. Shulman surveyed the feet of 5128 Chinese and Indian habitually barefoot (some would sometimes wear a very minimal sandal) volunteers and discovered very few foot defects (Shulman, 1949); far less foot defects compared to conventionally shod populations. There are many limitations to comparing populations from different parts of the world, but these findings suggest that barefoot walking is healthier. This is supported by another study that found fewer incidents of foot deformities in Chinese barefoot walkers than their shod counterparts within the population (Sim-

Fook and Hodgson, 1958). This has led some researchers to believe that being habitually barefoot is healthier than being habitually shod (Mafart, 2007, Zipfel and Berger, 2007).

A myriad of studies investigating the influence of footwear on habitually conventionally western shod populations exist. There is a plethora of studies comparing shod and barefoot running (Lieberman et al., 2010, Kelly et al., 2016, Kulmala et al., 2018, Altman and Davis, 2012, De Wit et al., 2000, Squadrone and Gallozzi, 2009, Divert et al., 2005), to name just a few. However, this thesis is on the influence of footwear properties during walking, not running. A great deal of work has also been put into occupational footwear. For example, studies investigated the influence of insole type and degradation in military boots while marching and running (Windle et al., 1999, House et al., 2002, Dixon et al., 2003). Further research is required for the influence of footwear on daily walking.

1.5. Current literature on the influence of footwear on gait characteristics and foot function for daily walking

There is limited research investigating the influence of footwear during walking. The studies that do typically compare gait characteristics between barefoot, conventionally shod and/or minimally shod walking to define the differences between the two or more of these walking conditions. Studies that investigate the influence of footwear on foot function typically either introduce an unfamiliar footwear to participants as an intervention for a prospective cohort study in order to compare foot function pre and post intervention period or compare the foot functions of participants with different footwear use history.

1.5.1. Barefoot and Shod Gait Characteristics

The current literature characterises gait characteristics using the following methods: spatial-temporal metrics, kinematics, kinetics, and plantar pressures. A systematic review has been published on barefoot and conventionally shod gait characteristics that covers all the above results (Franklin et al., 2015). This section reviews the literature reviewed within the Franklin et al. (2015) study as well as the publications that have come out since then.

The spatial-temporal metrics characterise the timing and placement of foot falls. Spatial-temporal metrics describe general gait trends through time. They are typically measured via 3D motion capture techniques. Spatial-temporal metrics include walking speed, stride length, stride width, stride frequency, gait cycle time and duty factor.

Many studies have found spatial-temporal differences between barefoot and shod walking (Wolf et al., 2008, Wirth et al., 2011, Oeffinger et al., 1999, Moreno-Hernández et al., 2010, Lythgo et al., 2009, Keenan et al., 2011, Petersen et al., 2020, Dames and Smith, 2016). Most of these studies found walking barefoot reduced stride and/or step length when compared to conventionally shod walking. This means that hip extension and/or flexion is likely to greater while walking conventionally shod.

Some studies found a faster walking cadence for walking barefoot (Lythgo et al., 2009, Moreno-Hernández et al., 2010, Wolf et al., 2008, Wirth et al., 2011) as well as stance time decreasing (Moreno-Hernández et al., 2010, Lythgo et al., 2009) when compared to conventionally shod walking. Studies with larger study populations found walking speed to decrease during barefoot walking as well (Wirth et al., 2011, Moreno-Hernández et al., 2010, Lythgo et al., 2009). Other studies that reported on walking speed found no significant difference between barefoot and conventionally shod walking, but had smaller study populations (Wolf et al., 2008, Oeffinger et al., 1999). Habitually barefoot communities' spatial temporal metrics have also been investigated. Griffin et al. (2010) found greater contact time during stance phase and slower gait in habitually barefoot individuals while walking, compared to habitually conventionally western shod participants. Overall spatial-temporal comparisons between barefoot and conventionally shod walking are well documented in the current literature, and in agreement one another. Therefore, the barefoot and conventionally shod walking spatial-temporal comparisons within this thesis should mirror that of the current literature. This is reflected in the hypotheses of this thesis, shown at the end of this current chapter.

The current literature investigating the spatial-temporal metrics of minimally shod walking to other walking conditions is limited. Wirth et al. (2011) found minimally shod walking stride length to be a significant intermediate between barefoot and conventionally shod walking, and minimally shod and barefoot walking to be similar overall. In contrast, Wolf et al. (2008) found no differences between stride length, walking speed or duty factor for minimally or conventionally shod walking, suggesting minimally shod walking is more like conventionally shod walking than barefoot walking. To the best of our knowledge the only other study to investigate the spatial-temporal metrics of minimally shod walking of habitually conventionally western shod participants was Petersen et al. (2020). Petersen et al. (2020) found stride length variability reduced while walking minimally shod as opposed to barefoot. A finding that suggests minimal footwear improves walking stability. The current literature of spatial-temporal characteristics of minimally shod walking in relation to barefoot and conventionally shod walking for conventionally western shod communities is limited and the only safe conclusion that can be drawn from it is that minimal footwear can reduce stride length variability while walking in comparison to barefoot walking. The other spatial-temporal observations regarding this topic are currently inconclusive. This thesis aims to provide definitive insight into minimally shod walking spatial-temporal characteristics by testing the hypotheses minimally shod walking will be a significant intermediate between barefoot and conventionally shod walking for an array of spatial-temporal variables. These hypotheses are shown at the end of this chapter, along with the rest of the thesis hypotheses.

Habitually barefoot and or minimally shod individuals were found to have no change in walking velocity between walking barefoot and in their indigenous footwear (Willems et al., 2017). This is backed up by another study that found walking barefoot comparable to walking in flip-flops (Price et al., 2014). Given that minimally shod walking for conventionally western shod communities is likely to be slightly faster than barefoot walking yet habitually barefoot and or minimally shod communities exhibit similar walking velocities while both barefoot and minimally shod it is likely that sufficient regular use of minimal footwear in conventionally western shod populations will reduce minimally shod walking speed in the at population.

Kinematics is the study of the motion of objects, so human kinematics is simply the study of the motion of humans, without reference to the forces underlying these motions (that is the domain of kinetics). Human kinematics technically encompasses spatial-temporal metrics, but the literature uses the term to describe more detailed gait characteristics than spatial-temporal metrics. Human walking kinematics typically describes the angular motion of joints throughout the gait cycle. It is typically measured via 3D motion capture techniques. Typically, reflective markers are attached at key anatomical landmarks so that participant motion can be captured by an infrared camera system. There will always be multiple cameras positioned in different locations that are focused in on the walkway with different angles in order to construct a 3D model based off of the reflective markers. Studies have found lower limb joint angular motion differences between barefoot and shod walking. Walking barefoot has been shown to cause flatter foot placement during initial contact caused by increased plantarflexion about the ankle joint complex when compared to conventionally shod walkers (Zhang et al., 2013, Oeffinger et al., 1999, Dames and Smith, 2016). Interestingly, the same finding was found between walking barefoot and walking in sandals and flip-flops (Zhang et al., 2013, Morio et al., 2009, Chard et al., 2013). Sandal and flip-flop type footwear is similar to minimal footwear, in terms of construction. The largest difference between sandal or flip-flop type footwear and minimal footwear or being barefoot is the presence of a cushioned, a relatively stiff sole, and in some cases a positive heel-to-toe offset (and walking in flip-flops requires toe flexion due to its more limited upper when compared to minimal footwear). This suggests plantar flexion about the ankle during initial contact is related to the level of cushioning, the stiffness of a sole, and/or heel-to-toe offset. Horvais and Samozino (2013) determined heel-to-toe offset is the determining factor of ankle plantar flexion magnitude at initial contact when running, as opposed to heel height. Neither Chard et al. (2013), Morio et al. (2009) or Zhang et al. (2013) reported heel-to-toe offset for the sandals/flip-flops. However, on inspection of the images provided within each study of these footwear it is clear that only the sandal in the Zhang et al. (2013) study can be considered to have a zero heel-to-toe offset. It is therefore likely that the greatest determinant for ankle plantar flexion at initial contact in walking is also the heel-to-toe offset of footwear. Minimal footwear also has a zero heel-to-toe offset, therefore minimally shod walking peak plantar flexion angle at initial contact are likely to be similar to those of barefoot walking, with conventionally shod walking exhibiting a lessor peak plantar flexion angle at initial contact.

Walking barefoot has also been shown to increase knee flexion during initial contact (Zhang et al., 2013, Oeffinger et al., 1999). This supports the theory of the lower limb joints regulating compliance to maintain optimal body stiffness, as seen during running (Farley et al., 1998, Ferris and Farley, 1997, Ferris et al., 1998); additional knee flexion during barefoot walking maintains a comfortable body stiffness without the presence of compliant cushioning from footwear. Medial and lateral wedge orthoses in footwear were found to have no significant effect on knee or hip kinematics when compared to footwear without orthoses (Nester et al., 2003), further suggesting that it is the level of cushioning and/or heel-to-toe offset that has the greatest influence on knee kinematics. This means that knee flexion at initial contact is likely to be greater than conventionally shod walking when minimally shod walking, in addition to barefoot walking. The range of motion for both the ankle and the knee joint is greater during the stance phase when conventionally shod (Zhang et al., 2013). Dames and Smith (2016) didn’t find differences between barefoot and conventionally shod walking ankle range of motion, but knee and hip range of motion was shown to be greater while conventionally shod walking. The increased hip range of motion while walking conventionally shod found by Dames and Smith (2016) supports the findings of the previously discussed literature regarding conventionally shod walking having a greater stride and/or step length (Franklin et al., 2018). This is because the hip is effectively the central pivot of the lower limbs, therefore greater flexion, extension, or both flexion and extension of the hip is required to position the feet further from one another resulting in a greater step length and ultimately stride length. Given that Dames and Smith (2016) have only reported the range of motion for the lower limb joint angles it is not possible to identify joint angle characteristics throughout the gait cycle. Therefore, it is currently not possible to specify whether hip flexion or extension is responsible for the increased step length while conventionally shod, or even at which point of the gait cycle peak hip angles are greater. Both Oeffinger et al. (1999) and Zhang et al. (2013) have presented barefoot and conventionally shod walking comparisons for both sagittal ankle angles throughout stance phase, however hip angles are neglected. In addition to this only Oeffinger et al. (1999) represents swing phase. Interesting observations from both studies can be made such as peak ankle plantarflexion during loading response is greater while barefoot as opposed to conventionally shod walking, and peak dorsiflexion during terminal stance is greater while conventionally shod as opposed to barefoot walking. However, no statistical analysis has been conducted to prove these observations are real differences. Based on the current literature it is not possible to fully detail the differences between barefoot and shod walking lower limb joint kinematics. It would be greatly beneficial to the footwear biomechanics community to have a centralised and fully detailed comparison between barefoot and shod walking lower limb joint angles throughout the gait cycle that highlights statistically significant differences between the walking conditions, to effectively characterise the influence footwear has on walking gait characteristics.

To the best of our knowledge, only Wolf et al. (2008) has investigated minimally shod walking kinematics compared to barefoot and conventionally shod walking. This study did not investigate total lower limb extremity kinematics like the previously discussed kinematics literature but rather focused on foot kinematics. Wolf et al. (2008) found that minimally shod walking foot kinematics are more similar to conventionally shod walking foot kinematics than to barefoot walking. Out of all the foot kinematic metrics reported, only the percentage change in forefoot width throughout the gait cycle was significantly greater while minimally shod walking when compared to conventionally shod walking (Wolf et al., 2008). An attribute that is likely caused by the forefoot having greater room to move as a result of the wider toe box area typical of minimal footwear. This study comprehensively shows minimally shod walking foot kinematics in comparison to barefoot and conventionally shod walking kinematics. As this is the only study to investigate minimally shod walking kinematics of any kind it also highlights the need to investigate overall minimally shod walking lower limb joint kinematics in relation to both barefoot and conventionally shod walking.

The Wolf et al. (2008) study used the Heidelberg foot measurement method to generate foot kinematics (Simon et al., 2006). There exists a plethora of foot kinematic models (Carson et al., 2001, De Mits et al., 2012, Kidder et al., 1996, Leardini et al., 1999, Leardini et al., 2007, Simon et al., 2006), yet the use of kinematic foot models to investigate the influence of shod walking is limited (Arnold and Bishop, 2013). Morio et al. (2009) found barefoot walking eversion of the forefoot was greater and it occurred faster than conventionally shod walking. This suggests that conventional footwear restricts natural forefoot motion. Foot kinematics can offer valuable insight into the influence of footwear on walking biomechanics and given the current limited literature it would be beneficial to incorporate such an analysis into this thesis.

Kinetics with regards to human walking is the study of forces associated with walking. It describes joint moments and powers as well as ground reaction forces. The current literature records these attributes via accelerometers or force plates on their own or in combination with 3D motion capture techniques. Kinetic analysis between barefoot and conventionally shod walking shares little agreement between studies and at times has brought up contradictory results. Oeffinger et al. (1999) found walking barefoot increased hip extensor moments at terminal swing and decreased knee flexor moments at loading response when compared to conventionally shod walking, whereas Keenan et al. (2011) found walking barefoot reduced hip extensor moments at loading response, reduced hip flexor moments at terminal stance, and increased knee flexor moments at loading response. This contradiction in the literature could be the result of differences in study methodology – Keenan et al. (2011) recorded treadmill walking and controlled walking velocity whereas Oeffinger et al. (1999) investigated over ground walking and allowed for a self-selected walking pace. Dames and Smith (2016) controlled over ground walking speed and found both barefoot walking hip and knee extensor moments (at loading response and toe off respectively) to be greater than conventionally shod walking. Zhang et al. (2013) also controlled over ground walking speed and found no differences for barefoot and conventionally shod walking knee flexion moments (Zhang et al., 2013). Their study also found some type of conventional footwear, in this case sandals and flip-flops, increased hip flexion moments in late stance when compared to barefoot walking, whereas walking in shoes had no significant influence on hip flexion moments when compared to barefoot walking (Zhang et al., 2013).

Ankle flexion moments showed more agreement within the literature than the hip and knee joint moment metrics and differences in the literature were still present. A few studies found no differences in ankle flexion moments while walking barefoot and conventionally shod (Zhang et al., 2013, Keenan et al., 2011, Dames and Smith, 2016), whereas Oeffinger et al. (1999) found barefoot walking had reduced ankle peak plantarflexion moment during terminal stance when compared to conventionally shod walking. There was also slight disagreement in the literature with regards to ankle eversion moments: Keenan et al. (2011) found barefoot walking ankle inversion moments to be greater than conventionally shod walking at the end of stance phase (Keenan et al., 2011), Zhang et al. (2013) mostly agreed, finding barefoot walking ankle inversion moments to be greater than some types of conventional footwear, in this case sandals and flip-flops, and Oeffinger et al. (1999) reported no differences. Given that the Oeffinger et al. (1999) study used over ground walking at a self-selected pace, it is likely moment results within this thesis will exhibit joint moment results closer to Oeffinger et al. (1999) as the study within this thesis will also use over ground walking at a self-selected pace during kinematic and kinetic experimentation.

There is limited research on shod and barefoot walking's influence of the lower extremities' joint powers, and the current literature has not reached a consensus on its influence. Oeffinger and colleagues found ankle power absorption during terminal stance to be greater while conventionally shod (Oeffinger et al., 1999), whereas Dames and Smith (2016) reported no differences between barefoot and conventionally shod walking ankle power. Dames and Smith (2016) also found both barefoot walking peak hip and knee power absorption during terminal stance to be greater than conventionally shod walking, whereas Oeffinger et al. (1999) only reported that knee power generation was greater at initial contact while walking barefoot (Oeffinger et al., 1999). Given that the literature comparing shod and barefoot lower limb joint moments and powers is so limited and conflicting it isn't possible to use this literature to predict the results of this thesis. In addition to this, no studies investigating minimally shod walking lower extremity joint moments and/or powers have been conducted. Ideally an exploratory study needs to be conducted that compares all lower limb joint kinetics for barefoot, minimally shod and conventionally shod walking in order to best characterise in the influence of footwear on walking gait characteristics.

Further kinetic contradictions between barefoot and conventionally shod walkers were found regarding propulsive ground reaction forces. Some studies have found barefoot walking reduces the impact during heel strike (Sacco et al., 2010, Keenan et al., 2011) whereas other studies have reported an increased impact (Lafortune and Hennig, 1992, Shorten and Mientjes, 2011, Voloshin, 1988, Voloshin and Wosk, 1980). This is potentially problematic as excessive tibial shock can cause wear to the knee joint (Voloshin and Wosk, 1980).

Studies comparing minimally shod walking ground reaction forces to barefoot and conventionally shod walking also exist. Addison and Lieberman (2015) found sole hardness increases the loading impact rate while walking, with minimally shod walking having the fastest impact loading rate. Interestingly, Addison and Lieberman (2015) also showed vertical impulse and effective foot mass at impact were lower while minimally shod when compared to the conventionally shod walking conditions. Vertical ground reaction forces while walking in minimal footwear has been found to be different from walking barefoot. Both indigenously minimally shod and conventionally shod populations have significantly higher impact peaks when walking in minimal footwear as opposed to walking barefoot

(Wallace et al., 2018). Willems et al. (2017) found greater differences between habitually barefoot/minimally shod individuals walking over different terrains than between barefoot walking and the indigenous footwear. The differences that were found between barefoot walking and these indigenous shoes were only very slight and Willems concluded that this type of indigenous footwear “mimics” walking barefoot and noted comparisons should be made between indigenous minimal footwear and western minimal footwear (Willems et al., 2017).

Plantar pressure measurements otherwise known as pedobarographic measurements are non-invasive and are quick and easy to collect experimentally, however the analysis requires high technical and methodological knowledge (Deschamps et al., 2015). They are technically a type of kinetic analysis but for the purposes of this research are classified as its own separate entity. Plantar pressure measurements are often used to aid in clinical decisions related to the foot and ankle (Bennetts et al., 2013, Razak et al., 2012).

Plantar pressure measurements are typically collected with plantar pressure mats. Plantar pressure mats are similar to force plates but have a matrix of load transducers embedded into the plate as opposed to just a few. The load transducers record the force it experiences in its local area and calculated the pressure in that area when a plantar pressure mat is walked over. Plantar pressure insoles can also be used to gather plantar pressure information (Warne et al., 2014, Dixon, 2008) however care must be taken when using absolute force values from the insoles (Low and Dixon, 2010). The insoles work in a similar way to plantar pressure mats but are placed within participant shoes. There are four analysis techniques of pedobarographic measurements that are employed:

- Region of Interest analysis: Which takes an aggregate of plantar pressures within pre-defined anatomical regions of the foot (Bennetts et al., 2013, De Cock et al., 2006).

- Centre of Pressure (CoP) trajectories: Which compress the spatial information of the plantar pressure data through time (De Cock et al., 2008, Keijsers et al., 2016) and has been proven a useful method for evaluating footwear influence on gait characteristics (Dixon, 2006).

- Pedobarographic statistical parametric mapping (pSPM): Which compress the temporal aspect of the pedobarographic measurement and optimally transform the resultant 2D prints so that all prints overlap and can be compared to one another at the pixel level, absent of pre-determining anatomical regions. The region of interest analysis method can draw incorrect conclusions dew to the sensitivity of the anatomical regions definitions (Pataky et al., 2008). CoP trajectories can also lead to incorrect conclusions due to the spatial normalisation of the prints. However, when combined with the optimal transformations used for pSPM this issue is greatly reduced (Pataky et al., 2014). pSPM does not require any assumptions about anatomy as all the prints are registered to one another using a genetic optimisation algorithm so that all prints optimally overlapped (Pataky and Goulermas, 2008).

- STAPP (Spatiotemporal analysis of full plantar pressure videos using statistical parametric mapping) is a new pedobarographic analysis technique has been developed recently that can pick up differences in comparisons that the other method might miss as it requires no sub-sampling (Booth et al., 2018). This method is very new but is likely to become the new gold standard for plantar pressure analysis. This method was not available when the data analysis for this research was conducted.

These plantar pressure analysis techniques have been used to assess differences between shod and unshod walking. Carl and Barrett (2008) analysed plantar pressure measurements gathered from plantar pressure insoles of barefoot and conventionally shod walking, via region of interest analysis. The study found greater peak plantar pressures under the calcaneus and metatarsal heads during barefoot walking in comparison with walking in flip-flops or athletic footwear (Carl and Barrett, 2008). D'Août et al. (2009) analysed habitually barefoot, indigenously minimally shod, and habitually conventionally western shod participants plantar pressure measurements gathered from plantar pressure mats while participants walked barefoot and/or shod, via pSPM. This study found habitually barefoot walkers have lower peak pressures overall when compared to habitually minimally shod and western conventionally shod walkers, due to the wideness of habitually barefoot walkers' feet and that the plantar pressure distributed more evenly (D'Août et al., 2009). Therefore, it seems that experience of barefoot walking improves barefoot walking plantar pressure distributions. D'Août et al. (2009) also observed habitual barefoot walkers to have relatively lower plantar pressure distributions at the ball and heel of the foot and higher relative distributions at the midfoot and toes (D'Août et al., 2009). This suggests that habitual barefoot walkers distribute plantar pressure more evenly over their feet. This conclusion is drawn from the same population but most of the literature like this do not have the different footwear wearing habits within the same population. The authors notes that studies using similar populations investigating the same areas are required in the future (D'Août et al., 2009). Cudejko et al. (2020) used CoP analysis from measurements gathered from plantar pressure mats to assess stability while in barefoot, minimally shod and conventionally shod. This study found stability was greatest while minimally shod (Cudejko et al., 2020). Cudejko et al. (2020) reviewed both static and dynamic (walking) CoP results of three of these conditions to draw this conclusion. The dynamic results presented only show the maximum medial-lateral displacement and mean medial-lateral velocity throughout stance phase. These measurements unfortunately offer very limited insight into gait characteristics during stance phase. Currently no study has compared detailed CoP trajectories for walking barefoot and shod, for either medio-lateral or anterior to posterior displacement throughout stance phase. This type of study could increase insight into the influence of footwear on gait characteristics during walking. As there is currently no literature that has done this kind of study so far it is more difficult to predict the outcome of such a study. However, given that conventional footwear has far stiffer soles than minimal footwear and the bare foot has no external restrictions, it is likely that anterior to posterior CoP trajectories will progress through stance phase from heel to toe most smoothly while barefoot and least while conventionally shod, with minimally shod walking CoP trajectory being an intermediate.

All the conventionally western shod participants in the above studies had no experience in minimal footwear prior to the study. There is currently no study that investigates the gait characteristics of habitually conventionally western shod participants once experience has been gained in minimal footwear. Experience in minimal footwear is likely to have an impact on conventionally western shod participants minimally shod gait characteristics, as minimally shod gait characteristic differences exist between habitually conventionally shod participants and indigenously minimally shod participants. Hollander et al. (2017b) systematic review on the long-term influence of habitual barefoot walking and running noticed this gap in the literature and urged for future research to conduct prospective studies investigating habitually conventionally western shod participants transitioning to minimal footwear. Prospective cohort studies have been conducted on gait characteristics associated to transitioning to minimally shod running (Moore et al., 2015) yet currently none have been done for walking.

1.5.2. The long-term influence of Barefoot and Shod walking on foot function

Many researchers have suggested habitual use of footwear causes pathological changes (Hoffmann, 1905, Zipfel and Berger, 2007, Yan et al., 2013, Frey et al., 1993). For example, adults who began to wear closed toe shoes before the age of six were more likely to have flat feet in adult life than those who did not (Sachithanandam and Joseph, 1995). Rao and Joseph investigated static footprints of a large sample of habitually shod and barefoot children. The habitually barefoot children showed less incidences of flat feet (Rao and Joseph, 1992). This is also supported by another study, where a sample of Congolese children living in areas where it is custom to walk barefoot, showed fewer cases of having flat feet (Echarri and Forriol, 2003). Flat foot is characterised by a particularly low longitudinal arch height (Mosca, 2010) and/or lower stiffness during walking (DeSilva and Gill, 2013, Saraswat et al., 2014). Arch stiffness is of particular importance because arch stiffness increases medial-lateral force transfer and medial forefoot propulsion in human walking

(Bates et al., 2013). Even though habitually barefoot walkers show less signs of flat feet there is less agreement on the long-term influence of footwear on arch stiffness. Holowka et al. (2018) found indigenously minimally shod participants' longitudinal arch stiffness to be greater than habitually conventionally western shod participants', whereas Kadambande et al. (2006) compared habitually barefoot and/or minimally shod participants' foot anthropometrics with regards to foot compliance and did not report on longitudinal arch stiffness. There is also disagreement in the literature on the long-term influence of footwear on longitudinal arch height. Some studies found habitually barefoot and/or indigenously minimally shod participants had greater static longitudinal arch height than habitually conventionally western shod participants (Lieberman, 2014, Hollander et al., 2017a), whereas D'Août et al. (2009) found no differences in longitudinal arch height. However, D'Août et al. (2009) noted that the variation in longitudinal arch heights were much less varied in the habitually barefoot group and much more varied in the habitually conventionally western shod group. This suggests the habitually conventionally western shod communities are more prone to extreme foot morphologies that can result in foot pathologies than habitually barefoot communities.

Conventional footwear has also been shown to restrict the natural motion of the barefoot by imposing a specific foot motion during the terminal phase (Morio et al., 2009). Conventional footwear often has a restrictive toe box area to give the footwear a "fashionable" thinner or even pointed end. This restrictive toe box area is believed to contribute to toe deformities such as hallux valgus (Al-Abdulwahab and Al-Dosry, 2000). This is particularly problematic for older people, as 66% of elderly population have feet significantly wider than much of the conventional footwear available (Chantelau and Gede, 2002). Studies have shown habitually barefoot communities to have relatively wider feet than habitually conventionally western shod communities (D'Août et al., 2009, Shu et al., 2015, Ashizawa et al., 1997, Hollander et al., 2017a, Hollander et al., 2017b). Shu et al. (2015) also discovered their habitually barefoot participants have a more spread-out hallux compared to habitually conventionally western shod participants. This agrees with another study that found, conventionally shod Europeans have a significantly more laterally orientated hallux angle than a sample of habitually barefoot Nigerians (Barnicot and Hardy, 1955).

Cross-population studies have limitations when comparing the two (or more) populations. These studies cannot rule out the cultural, dietary, and genetic differences as co-variables that might influence foot function alongside footwear habits. Prospective cohort studies are typically considered a more powerful type of study as they eliminate the potential co-variables associated with cross-population studies. Unfortunately, there are no prospective cohort studies investigating foot morphology differences as a result of changing footwear habits, however some studies have reported on changes in foot strength as a result of transitioning to minimal footwear.

Longitudinal studies have shown foot strength can be increased by performing sports in minimal footwear for healthy adults (Miller et al., 2014, Goldmann et al., 2013, Chen et al., 2016, Johnson et al., 2016). One study even found that walking in minimal footwear for an 8-week period is as effective as foot strengthening exercises for the same time period, in increasing foot muscle strength and size (Ridge et al., 2019). Another study found foot strength to be significantly greater in an indigenously minimally shod population compared to the conventionally shod one (Holowka et al., 2018). The current literature agrees that long-term use of minimal footwear increases foot strength, yet the time-period required to return to the naturally strong foot for healthy habitually conventionally western shod adults transitioning to minimal footwear is unknown.

1.6. Aims and Thesis Structure

There are clear gaps based off the current literature regarding barefoot, minimally shod, and conventionally shod gait characteristics and foot function. At times, the literature can even be contradictory. A full centralised lower limb joint kinematic and kinetic comparison between barefoot, minimally shod, and conventionally shod walking has never been done before. In addition to this no study has considered the potential influence gaining experience for walking in minimal footwear has on both gait characteristics and foot function and how the two may relate to one another. This research aims to use many of the techniques used by the previously literature to conduct very comprehensive research on barefoot, minimally shod, and conventionally shod gait characteristics and foot function, in order to answer these previously unanswered points.

This section addresses the research questions, aims and objectives, and hypotheses formulated based on the current literature relating to this research project: the influence of minimal footwear on the biomechanics of walking. The section goes on to describe how the aims and objectives are incorporated into the thesis structure.

1.6.1. Research questions

1. What differences exist between barefoot, minimally shod, and conventionally shod walking in healthy adults?

2. Can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function?

3. What are the long-term effects of walking in minimal footwear?

1.6.2. Aims and Objectives

Three central aims were devised to tackle the research questions. These aims can be broken down into six and eight objectives, respectively. The research aims and objectives are as follows:

1. Investigate differences between barefoot, minimally shod, and conventionally shod walking in healthy adults.

    a. Quantify the conventional and minimal type footwear properties used within this project.

    b. Quantify key biometrics from all participants within this project.

c. Investigate the spatial and temporal plantar pressure differences between barefoot, minimally shod, and conventionally shod walking of a conventionally western shod community.

d. Investigate the spatial-temporal gait characteristics differences between barefoot, minimally shod, and conventionally shod walking of a conventionally western shod community.

e. Investigate the lower limb kinematic and kinetic differences between barefoot, minimally shod, and conventionally shod walking of a conventionally western shod community.

2. Investigate the influence of habitually conventionally shod healthy adults transitioning to minimal footwear, with regards to their gait characteristics and foot function.

    a. Design a prospective study that monitors habitually conventionally shod adults transitioning to minimally shod walking.

    b. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on plantar pressure distributions while walking barefoot, minimally shod, and conventionally shod.

    c. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on temporal plantar pressure patterns while walking barefoot, minimally shod, and conventionally shod.

    d. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on spatial-temporal gait characteristics while walking barefoot, minimally shod, and conventionally shod.

e. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on lower limb kinematics while walking barefoot, minimally shod, and conventionally shod.

f. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on barefoot foot kinematics.

g. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on foot morphology.

h. Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on foot strength.

3. Investigate the long-term effects of walking in minimal footwear.

    a. Investigate the spatial plantar pressure differences between barefoot, and minimally shod walking of habitually minimally shod communities.

    b. Investigate the spatial and temporal plantar pressure patterns of experienced minimally shod walkers from a habitually conventionally western shod background.

    c. Quantify foot strength of an indigenously minimally shod community.

    d. Quantify foot strength of experienced minimally shod walkers from a habitually conventionally western shod background.

    e. Quantify the foot morphology of experienced minimally shod walkers from a habitually conventionally western shod background.

1.6.3. Hypotheses

Hypotheses were formed based on the objectives. These hypotheses and the objectives they relate to are shown in Table 1.1.

Table 1.1: Research hypotheses and which objective they relate to. The objectives and hypothesis are also colour coded to indicate which chapter they belong to. Chapter 2 = blue, chapter 3 = green, chapter 4 = orange and chapter 5 = red.

Objective	Hypotheses
Investigate the spatial and temporal plantar pressure differences between barefoot, minimally shod, and conventionally shod walking in conventionally western shod communities.	Minimally shod walking peak plantar pressure will be less than barefoot walking and greater than conventionally shod walking for habitually conventionally western shod adults.
	Inexperienced minimally shod walkers will heel strike most distally when walking barefoot and least while walking conventionally shod, with minimally shod walking as an intermediate for habitually conventionally western shod adults.
Investigate the spatial-temporal gait characteristics differences between barefoot, minimally shod, and conventionally shod walking of a conventionally western shod community.	Walking speed will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate for habitually conventionally western shod adults
	Stride length will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate, for habitually conventionally western shod adults.

Investigate the lower limb kinematic and kinetic differences between barefoot, minimally shod and conventionally shod walking of a conventionally western shod community.	Conventionally shod walking will produce a greater ankle dorsiflexion angle at initial contact than both barefoot and minimally shod walking.
	Shod walking peak ankle, knee and hip angles will be greater than barefoot walking.
	Peak ankle plantarflexion moment will be greatest while walking conventionally shod and lowest while barefoot.
	Peak power will be lowest while walking barefoot, and greatest while walking conventionally shod.
Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on plantar pressure distributions while walking barefoot, minimally shod, and conventionally shod.	Six months of regular minimal footwear use will produce minimally shod walking peak plantar pressure distributions statistically indistinguishable from their barefoot plantar pressure distributions.
Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on temporal plantar pressure patterns while walking barefoot, minimally shod, and conventionally shod.	Six months of regular minimal footwear use will lead to minimally shod walking heel-to-toe plantar pressure progression throughout stance phase being closer to that of barefoot walking.

Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on spatial-temporal gait characteristics while walking barefoot, minimally shod, and conventionally shod.	Six months of minimal footwear use will result in a reduction of walking speed while walking minimally shod. Six months of minimal footwear use will result in a reduction of stride length while walking minimally shod.
Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on lower limb kinematics while walking barefoot, minimally shod, and conventionally shod.	Six months of regular minimal footwear use will lead to minimally shod walking peak ankle, knee, and hip angles tending towards those of barefoot walking.
Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on barefoot foot kinematics.	Six months of regular minimal footwear use will increase dynamic foot spread about the ball of the foot while walking barefoot. Six months of regular minimal footwear use will increase arch stiffness while walking barefoot.
Investigate the influence of habitually conventionally western shod adults transitioning to regular	Six months of regular minimal footwear use increases foot width.

minimal footwear use on foot morphology.	
Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on foot strength.	Foot strength increases in conventionally western shod populations after using minimal footwear for daily activity after a six month period.
Investigate the influence of habitually conventionally western shod adults transitioning to regular minimal footwear use on foot strength.	Foot strength continues to increase in conventionally western shod populations if regular use of minimal footwear is maintained after a six month period.
Investigate the spatial plantar pressure differences between barefoot, and minimally shod walking of habitually minimally shod communities.	Normalised peak plantar pressure distributions in any shod condition will be equivalent to the barefoot walking condition for habitually minimally shod communities.
Quantify foot strength of an indigenously minimally shod community.	Conventionally western shod adults will have comparable foot strengths to habitually barefoot and/or minimally shod adults given sufficient minimally shod walking experience.
Quantify the foot morphology of experienced minimally shod walkers from a habitually conventionally western shod background.	Experienced minimally shod walkers will have greater foot width than minimally shod walkers.

1.6.4. Thesis Structure

The research project was carefully planned out to answer the central research questions and achieve the research aims and objectives. A study was designed to measure and record gait characteristics for barefoot, minimally shod, and conventionally shod walking in habitually western conventionally shod healthy adult participants. These gait characteristics would be quantified as a series of plantar pressure, kinematic and kinetic measurements taken using the University of Liverpool Gait Lab facilities. Participant history, biometrics, participant footwear properties, and foot strength was also evaluated in addition to gait characteristics. This would create a baseline for the barefoot, minimally shod, and conventionally shod walking of habitually conventionally shod healthy adults as well as their general biomechanics. These same participants would then take part in a prospective cohort study. Some of the participants would be allocated minimal footwear that they would be required to wear regularly for the duration of the longitudinal study, and the rest of the participants would continue with their habitual conventionally shod walking habits. All participants would record their activity for the duration of the intervention period. At the end of the longitudinal study all the participants would return to the Gait Lab for post-intervention period tests to repeat the same measurements following the same procedure employed in the pre-intervention period tests.

This prospective cohort study of habitually conventionally western shod participants is referred to as the Minimal Footwear Adaption (MFA) study throughout this thesis. This study effectively answers the first two research question and achieves the first two research aims, however the length of the intervention period was only six months. Six months was chosen as this is the maximum recommended lifespan of the minimal footwear allocated to the participants as well as the maximum feasible timespan to manage participant satisfaction and project time constraints. To gather more insight on the longer-term effects of minimally shod walking further studies were conducted on participants with greater minimally shod walking experience. A group of Experienced Minimally Shod (EMS) walkers from a habitually western conventionally shod background had plantar pressure and foot strength measurements taken following the same methodology used in the MFA study. The EMS participants had an average of two and a half years' minimally shod walking experience. Finally, Dr Catherine Willems, a supervisor and founder of the Future Footwear Foundation (the funding body for this research project) had collected plantar pressure measurements from three indigenously minimally shod communities while walking barefoot and in their indigenous footwear. She and Dr Kristiaan D'Août had also recorded barefoot, minimally shod, and conventionally shod plantar pressure measurements from habitually conventionally western shod Belgium participants. The indigenously minimally shod communities were South Indians from a rural village of Athani in the state of Karnataka, Sami Scandinavians from around Inari, Northern Finland, and a Ju|'hoan San at the Nyae-Nyae Concession Area, Otjizondjupa region, Namibia. These communities had been walking in their indigenous minimal footwear or barefoot walking for most of their lives. This study that investigated the plantar pressures of three indigenously minimally shod communities and one habitually conventional western shod community is referred to as the indigenous footwear study. I joined the project to help finish the data collection on the San community. I used this opportunity to finish off the plantar pressure measurements from the San group as well as taking foot strength measurements from a San sub-group. This San sub-group that had foot strength measurements taken, had some participant overlap with the San group that had plantar pressure measurements taken but should ultimately be considered as a separate group. Therefore, the San sub-group that had foot strength measured is referred to as the habitually barefoot and/or minimally shod (HBM) group.

It is therefore clear this thesis incorporates a sizable number of different participant groups, biomechanical analysis techniques, and a mix of cross-sectional and prospective studies designs. In order to best analysis results across groups, I predominantly divided the chapters by the key biomechanical measurements taken within this research project, plantar pressure, foot strength, and kinematics and kinetics. The only exception is the second chapter which focuses on the joint work between me and Dr Willems.

The story is told through these six thesis chapters. This Introduction chapter introduces the field of study. The second chapter focuses exclusively on plantar pressures from the indigenous footwear study and has been written with equal contribution by myself and Dr Catherine Willems, as she collected the data, and I conducted the analysis on the data and part of the writing (which is currently under review at Footwear Science). Chapters three to five focus on the MFA study. The MFA study are split into the techniques used within the longitudinal study. Chapter three investigates the influence of six months of regular minimally shod walking on foot strength. Chapter four investigates plantar pressure measurements of barefoot, minimally shod, and conventionally shod walking pre and post invention period. Chapter five investigates kinematics and kinetics of barefoot, minimally shod, and conventionally shod walking pre and post intervention period. The EMS study results are added to the MFA focussed chapters three and four, where the techniques used are the same, to speculate how additional time in minimal footwear can influence habitually minimally shod walkers. Chapter three also had a sub-group of the San HBM sub-group. Finally, chapter six is the conclusion chapter. The thesis chapters can be seen below:

- Chapter 1 – Introduction
- Chapter 2 – Plantar pressures in three types of indigenous footwear, commercial minimal shoes, and conventional western shoes, compared to barefoot walking (submitted for publication, Footwear Science).
- Chapter 3 – Daily activity in Minimal footwear increases foot strength (being prepped for publication, Scientific Reports)
- Chapter 4 – A prospective study on transitioning to regular minimal footwear use and its influence on plantar pressures in barefoot, minimally shod, and conventionally shod walking

- Chapter 5 – A prospective study on Transitioning to Regular Minimally Shod Walking and its influence on the Kinematic and Kinetic Characteristics of Barefoot, Minimally Shod and Conventionally Shod walking.

- Chapter 6 – Conclusion

The organigrams shown in Figure 1.11 and Table 1.2 details the types of analysis used in each chapter and shows the overall thesis structure clearly.

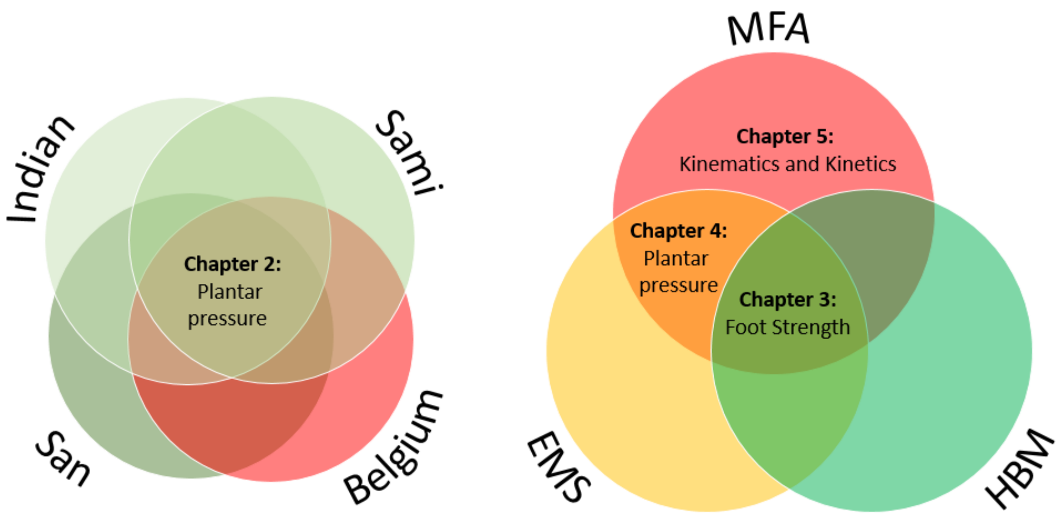

Figure 1.11: Organigram showing the participant groups involved in each of the central results chapters, as well as the central results focus of each of these chapters.

Table 1.2: Organigram showing the analysis types used on which populations in each of the thesis chapters. Numbers 2 – 5 refer to the chapter number.

Analysis Types	Participant groups							
	Indigenous footwear				MFA		EMS	HBM
	Indian	Sami	San	Belgium	Pre tests	Post tests		
Biometrics	2	2	2	2	3	3	3	3
Activity	-	-	-	-	3		-	-

Footwear properties	Spatial & Mass	2	2	2	2	3	3	3	-
	Mechanical	-	-	-	-	3	3	3	-
Participant history		-	-	-	-	3	3	3	-
Plantar pressure	Spatial	2	2	2	2	4	4	4	-
	Temporal	-	-	-	2	4	4	4	-
Foot strength		-	-	-	-	3	3	3	3
Kinematics & Kinetics	Spatial-temporal	-	-	-	-	5	5	-	-
	Lower limb joints	-	-	-	-	5	5	-	-
	Foot	-	-	-	-	5	5		-

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2. Chapter 2: Plantar pressures in three types of indigenous footwear, commercial minimal shoes, and conventional western shoes, compared to barefoot walking

2.1. Chapter 2 Covering page

2.1.1. List of Authors

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2.1.2. Author Contributions

Rory Curtis: Helped with collection of results from the Southern African Ju|'hoan San sub-group, analysed results, wrote the methods, results and discussion section, and edited the introduction.

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2.1.3. Chapter 2 Foreword

This chapter investigates the plantar pressures of three indigenously minimally shod communities and one habitually conventional western shod community and is referred to as the indigenous footwear study within the thesis. This chapter partially answers the third central research question (what are the long-term effects of walking in minimal footwear?) along with chapters three and four. Chapter two also tests the hypothesis, peak plantar pressure distributions in any shod condition will be equivalent to the barefoot walking condition for habitually minimally shod communities.

Much of the early work had already been completed by the time Rory Curtis started his PhD. Along with writing the literature review, analysing the results and writing up this chapter was one of the first tasks of the PhD. As a result, this chapter largely shaped the direction of the rest of the thesis. The results of this study showed no normalised peak plantar pressure distributions differences between barefoot and minimally shod walking for all three indigenously minimally shod communities. Yet temporal plantar pressure differences between barefoot and minimally shod walking of the conventionally western shod community existed. In addition to this, the literature showed minimally shod walking to exhibit biomechanical differences from barefoot walking (Franklin et al., 2015). However, this literature only focused on minimally shod walking for participants that did not have any experience in minimally shod walking. There was not any literature where conventionally western shod people gained experience in minimal footwear before investigating minimally shod walking gait characteristics. This led to the idea that gaining experience in minimally shod walking could lead to minimally shod walking gait characteristics the same as barefoot walking. This realization gave rise to three central research questions within this thesis and largely shaped the rest of the work within this thesis. In addition to this, this chapter evaluated the following hypothesis:

- Normalised peak plantar pressure distributions in any shod condition will be equivalent to the barefoot walking condition for habitually minimally shod communities.

2.2. Abstract

Humans evolved as barefoot walkers, and only started to use footwear recently in evolutionary history. It can be questioned what the effect is of footwear on gait. This effect has previously been studied for a range of conventional and athletic footwear, but this study focuses on indigenous footwear which does not have the features commonly associated with conventional footwear, such as a raised heel, a relatively narrow toe box, arch support, and a firm heel cup. We will assess whether such footwear can be considered functionally 'minimal' and simulate barefoot walking, by analysing spatial and temporal aspects of plantar pressure distribution.

We first compare the relative distribution of peak plantar pressure, using 2D Statistical Parametric Mapping, between four populations walking barefoot and shod with indigenous or commercial minimal shoes. We compared South Indians wearing sandal-like footwear ('Kolhapuri'), Northern Scandinavians wearing boot-type footwear ('Nuvttohat'), Southern African Ju|'hoan San wearing sandal-like footwear ('N!ang n|osi') and Western Europeans wearing a commercial minimal shoe, and their own conventional Western footwear. Within each population, indigenous and commercial barefoot footwear data were compared to barefoot walking. No statistically significant differences were found within-population between all footwear conditions and barefoot walking.

Second, we question whether there were differences in the timing of foot unroll between three footwear conditions (barefoot, commercial minimal, conventional Western) within one, Western, population. Using 1D Statistical Parametric Mapping, differences between these three conditions are shown, with conventional western footwear keeping a more distal CoP position during most of push-off phase.

Based on plantar pressure recordings, we conclude that all indigenous and commercial minimal shoes can functionally be considered 'minimal footwear', but with some differences to barefoot walking.

2.3. Introduction

Most people, especially adults, wear some form of footwear on a daily basis. Not surprisingly, a large body of work exists on biomechanical effects of footwear. These studies have focused predominantly on functional sports shoes, for instance for running (e.g. for injury prevention and performance enhancement; see Nigg (2010)) and on therapeutic footwear and/or orthotics for specific patient groups (e.g. neuropathic diabetic patients; see Bus et al. (2015)). Surprisingly, relatively little work has been done on daily walking, even though it is often suggested that daily footwear might have a large effect on long-term biomechanical health. Specifically high heeled shoes are problematic (Coughlin (1995), Frey (2000)) and even moderate heels have been suggested to have a negative effect on knee osteoarthritis (Kerrigan et al., 2005). Hallux valgus (bunions), one of the main foot problems especially in women ((Easley and Trnka, 2007), for a review, see Nix et al. (2012)) has been suggested to be strongly influenced by the adoption of stiff, heeled footwear (Mafart, 2007). Holowka et al. (2019) show that thick foot calluses in barefoot populations protect feet, like a shoe sole, while also allowing for good mechanoreception.

A large variety of footwear is used on a daily basis, ranging from thin-soled ballerina-style footwear, to rigid boots, to high heels; here grouped as 'conventional Western' footwear. Most types of habitually worn shoes do not claim to benefit health, and for some it has been clearly demonstrated that they actually impede health (e.g. high heeled shoes; Lee et al. (2001)). For those shoes that have not been shown to impede health (e.g. many daily worn shoes) it is unclear what their effect is.

Interestingly, what we consider 'daily', or 'conventional' footwear is a relatively recent and mostly Western invention. The oldest footwear found is approximately 8300 years old, a sandal made from plant fibre (Kuttruff et al., 1998). Archaeological findings show that also ancient Egyptians (e.g. Veldmeijer (2012), Sesana (2005)), ancient Romans (Allison, 2006, Cleland et al., 2007, Van Driel-Murray, 2001), and people in the Middle Ages used footwear that could be considered fairly 'minimal' to current standards. Shoes seemed to be non-constricting, there was no rigid heel cup, no arch support, little cushioning, and no elevated heel; features with potential biomechanical effects that are omnipresent in conventional Western footwear. For the purpose of this study, and in line with Sinclair et al. (2013), minimal footwear is defined as "Footwear providing minimal interference with the natural movement of the foot due to its flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices" (Sinclair et al., 2013). This definition outlines features of the shoe, but also the similarity of the resulting kinematics with barefoot walking.

Our recent adoption of conventional footwear in the last few centuries is in stark contrast with our anatomical, evolutionary development. Indeed, the oldest modern humans, *Homo sapiens*, were dated to approximately 200 000 years ago (McDougall et al., 2005) and hallmark characteristics of the modern human foot may have existed for several millions of years (Bennett et al., 2009). Since humans have been successful for such long periods, it can be questioned why we would need footwear with biomechanical effects (of course, footwear can serve other than biomechanical functions, e.g. protection from the cold or from sharp objects). Selection is likely to have acted very strongly on the human foot and on locomotor anatomy in general, so why would we need to interfere with their function for normal, daily locomotion? The foot is the only part of the body that is often judged to need biomechanical assistance. For instance, we do not use rigid clothing to help support the weight of the head, or gloves with biomechanical function to carry objects. In the rare cases where we do support parts of the body, e.g. when applying plaster casts to help fracture healing after trauma, muscle atrophy is observed (Appell, 1990). Experimental work to address these issues is impossible for obvious ethical reasons. However, the opposite approach can be used, and indeed it has been shown that athletes training in 'minimal' footwear gain foot muscle strength compared to those using conventional trainers (Goldmann et al., 2013, Miller et al., 2014). Using minimal footwear during daily life has been shown to both increase foot strength (Ridge et al., 2019), balance (Cudejko et al., 2020), and gait performance (Petersen et al., 2020).

Interestingly, even to date, several populations habitually use indigenous footwear that cannot be categorised as conventional Western. Such indigenous footwear has been in use for centuries. Based on their characteristics, the question arises if such footwear might be considered minimal. Therefore, in this study we set out to explore some of the biomechanical characteristics of walking in such footwear and we will compare them to a modern, commercially available type of minimal footwear, and to conventional Western footwear. Moreover, every shod condition will be compared within-subject to barefoot walking.

As a first biomechanical approach, we will use plantar pressure recordings to define the variation of the local distribution of pressures under the foot between indigenously or minimally shod walking, and conventionally shod as well as barefoot walking in healthy subjects.

Plantar pressure recordings have been used extensively to assess footwear. Most studies have used pressure sensitive insoles (e.g. Erdemir et al. (2005), Price et al. (2013), Sacco et al. (2009)) and there has been a strong focus on plantar pressure studies in diabetic patients with peripheral neuropathy, as there is a close relationship between high plantar pressure and ulcer formation (e.g. Armstrong et al. (2004), Frykberg et al. (1998), Barn et al. (2015)). The vast majority of studies have focused on running (e.g. De Wit et al. (2000), Paquette et al. (2013), Semal et al. (2017)) or on patient groups, and either studied barefoot walking (typically on a force plate) or shod walking (typically with pressure-sensitive insoles).

A previous field study compared walking with indigenous 'Kolhapuri' footwear to barefoot walking using foot-mounted accelerometery and goniometry (Willems et al., 2017). Based on these data, it was suggested that gait in these to conditions is overall similar, with some differences, including plantar/ dorsiflexion during stance. This indicates the movement of the foot throughout stance phase (foot unroll) is likely to be different between barefoot and shod walking. Therefore, the timing of foot unroll needs to be assessed, in addition to the overall pressure distribution.

Since any shoe likely provides some (even if minimal) amount of cushioning or pressure redistribution, we will test the null hypothesis that normalised peak pressure distribution in any shod condition will be equivalent to the barefoot walking condition. We expect that barefoot conditions will have greater normalised peak plantar pressures in the heel, the metatarsal heads and hallux. We also expect the temporal pattern of foot unroll in minimal footwear to be more similar to that of barefoot walking than to that of conventionally Western shod walking.

2.4. Materials and Methods

2.4.1. Subjects

Four populations were studied. An Indian population (N = 34) consisted of adult males and females from in and around the rural village of Athani in the state of Karnataka. A Scandinavian population (N = 36) consisted of male and female adults from in and around Inari, Northern Finland, of which a large fraction had a Sami background. A Namibian population (N=33) consisted of adult males and females with a Ju|'hoan San heritage at the Nyae-Nyae Concession Area, Otjizondjupa region. A Western population (N = 27) consisted of Caucasian male and females, mostly from Belgium. Of the 27 Western subjects 13 were also tested wearing their daily footwear, next to barefoot walking and with minimal footwear. Subjects with current or recent foot or lower limb injuries were excluded. Please see Table 2.1 and Table 2.2 for details.

Table 2.1: Indigenously shod groups' biometrics.

	Finland *n*=36		India *n*=34		Namibia *n*=33	
	Barefoot & reindeer boot		Barefoot & buffalo sandal		Barefoot and sandal	
	Male	Female	Male	Female	Male	Female

	Finland n=36 Barefoot & reindeer boot		India n=34 Barefoot & buffalo sandal		Namibia n=33 Barefoot and sandal	
	(n=14)	(n=22)	(n=20)	(n=14)	(n=20)	(n= 13)
Age (years)	52 ±15.8	46.3 ±17.6	38.3 ±10.2	39.6 ±8.4	39.2 ±15.7	37.6 ±11
Mass (kg)	83.9 ±14.2	65.2 ±14.1	59.4 ±11.5	55.4 ±9.8	44.7 ±8.3	46.2 ±9.1
Height (m)	1.74 ±0.07	1.61 ±0.09	1.64 ±0.05	1.49 ±0.05	1.57 ±0.09	1.53 ±0.08
BMI	27.6 ±4	25.3 ±5.2	22 ±3.8	24.8 ±3.6	18.1 ±2.4	19.7 ±3.6

Table 2.2: Western group's biometrics for both the sub-group that walked barefoot and minimally shod, and the sub-group that walked barefoot, minimally shod, and conventionally shod.

	Belgium barefoot & minimal n=27		Belgium daily footwear n=13	
	Male (n=15)	Female (n=12)	Male (n=6)	Female (n=7)
Age(years/mean)	38.9 ±11	33.5 ±11.7	36.8 ±9.7	33.5 ± 7.6
Mass (kg/mean)	84.1 ±14.2	58.7 ±6.3	82.5 ±11.7	58.4 ±5.9

	Belgium barefoot & minimal n=27		Belgium daily footwear n=13	
Height (m/mean)	1.82 ±0.06	1.69 ±0.06	1.81 ±0.06	1.69 ±0.05
BMI (mean)	25.7 ±3.6	20.6 ±1.3	26.4 ±2.4	20.7 ±1.4

2.4.2. Materials

The following types of footwear were used.

The first type of indigenous footwear is the South Indian ‘Kolhapuri’ footwear, a type of sandal that fits tightly onto the foot through an instep strap, and that has a thin sole made of vegetable tanned buffalo leather, typically with a very thin heel offset created by an extra layer of buffalo leather (Figure 2.1 A). The weight of an average single sandal is no more than 100 g (size 37F). This type of footwear is used in a very hot climate.

The second type of indigenous footwear is the Northern Scandinavian ‘Nuvttohat’ or reindeer boot, as traditionally worn by the Sami people. This boot is made entirely from vegetable tanned reindeer hide and used in an extremely cold climate. Dried grass is used for insulation (and may provide some cushioning), (Figure 2.1 B). The average weight of a boot is 220 g for a size 37F.

A third type of indigenous footwear is the sandal of the Ju|’hoan San, N!ang n|osi, used in the southern parts of Africa and made from antelope (giant eland) skin. It is worn by San people to protect the feet from hot sand and thorns. This indigenous sandal features a back-strap, and laces in between the big toe and other toes that keep the foot close to the sole (Figure 2.1 C). The weight of an average single sandal is about 150 g for a size 37F.

The minimal shoe (Vivobarefoot The One) is a sneaker with a 3mm puncture resistant outsole with a wide toe box to allow the toes to move freely (Figure 2.1 D). Low mass is an important feature of the four types of footwear (three indigenous and the minimal Western sneaker), together with the absence of arch support and heel support. Vivobarefoot 'The One' sneakers weighed 152 g for a size 37F.

An RSScan Footscan USB (0.5 m version) with Footscan USB 7 Gait software, running on a laptop PC, was used for all recordings. Calibration was regularly performed using the manufacturer's guidelines. Data were recorded at a temporal resolution of 300 fps and a spatial resolution of 7.62 mm along the long axis (walking direction) and 5.08 mm along the short axis (left-right) of the plate. The plate was installed indoors, on a flat and hard surface (see Figure 2.1 E, F, and H) when recording data of the Indian, the Scandinavian, and the Western subjects. For the recording of the Ju|'hoan San data the plate was installed outdoors, on an even terrain in their natural environment (See Figure 2.1 G).

Figure 2.1: A) Southern Indian "Kolhapuri" footwear. B) Northern Scandinavian "Nuvttohat"/reindeer boot. C) Ju|'hoan San "N!ang n|osi"/sandal. D) Vivobarefoot, "The One" trainers. E) Medio-lateral view of a Kolhapuri walking over the pressure mat while barefoot. F) Medio-lateral view of a Sami participant walking over the pressure mat while indigenously shod. G) Medio-lateral view of a San participant walking over the pressure mat while barefoot. H) Anterior view of a Belgium participant standing on the pressure mat while minimally shod.

2.4.3. Protocol

All subjects signed informed consent (approved by the University of Antwerp Ethics Committee; ethics number: B300201112278). We collected basic morphometrics (stature, mass, leg length as measured from the trochanter major to the ground, navicular height) as well as mechanical properties of the footwear in the Indian sub-study (for details, see Willems et al. 2017).

Subjects were instructed to walk barefoot at preferred speed over the pressure plate, with at least three steps before and after the plate. The effect of plate targeting was minimised by asking subjects to focus on a distant, eye-level mark. Several trials were recorded until we had three successful recordings for both the left and right foot. A recording was considered successful if there was no obvious acceleration or deceleration, any other maneuver (e.g. turning) and consisted of normal, comfortable walking.

The procedure was repeated for walking with Kolhapuri footwear (in the Indian sub-study), Nuvttohat footwear (in the Scandinavian sub-study), N!ang n|osi (in the Ju|'hoan San sub-study) and with commercial minimal footwear (Vivobarefoot 'The One') as well as the subject's own conventional footwear (in the Western sub-study) (Figure 2.1 C-E). A total of 1465 trials were used for this analysis.

2.4.4. Analysis

2.4.4.1. Preparation of the pressure records

The numerical pressure data (N/cm^2) of every cell over time (s) were exported from the acquisition software to ASCII text files and imported into MatLab 2017a, where all further analysis was performed.

In a first step, the pressure images were resampled from the non-square pressure cells into square (5 mm x 5 mm) pixels, and right feet were mirrored, assuming population-level symmetry.

From the resampled time series data (see Figure 2.2), we generated footprint plots determining peak pressure for each pixel over the course of the step.

This data was then normalised by taking the average pressure for these 2D peak pressure matrices and divided every pressure matrix by its respective average, generating relative plantar pressure distribution matrices. The data was normalised as plantar pressure mat calibration issues throughout the data collection process meant that absolute pressure values were incorrect and (at times) orders of magnitudes different between participants within the same population. By normalising the data in this fashion, barefoot and shod population comparisons focusing exclusively on relative plantar pressure distribution could be made. Once all the prints for each population had been normalised, steps four to seven of print pre-processing lined out in section "4.3.3.1. Print Pre-processing" of this thesis were followed. The pre-processed prints were then ready for linear image registration and analysis.

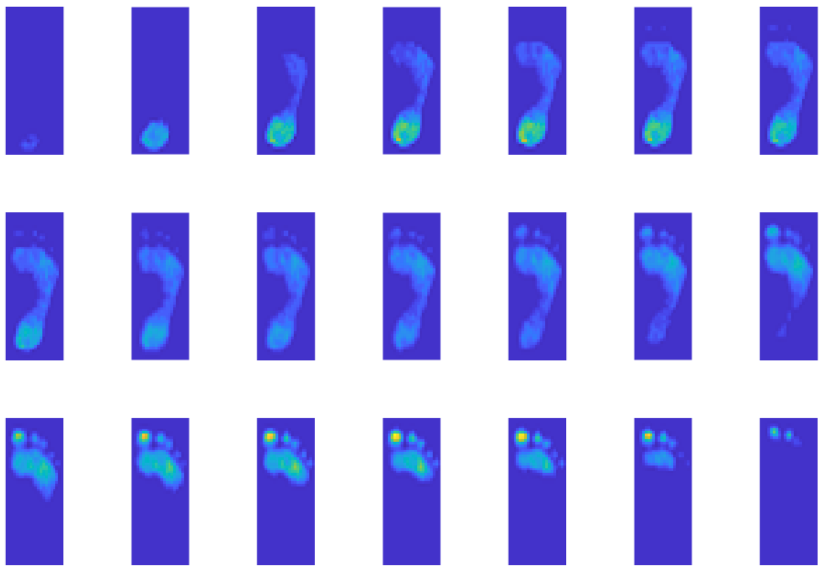

Figure 2.2: Example temporal roll-off in a barefoot walking South Indian Male. The full trail consists of 206 frames and the plots show the frames corresponding with 5% intervals, in which 0% corresponds to heel strike and 100% corresponds to toe-off (cooler colours represent relatively low pressure, warmer colours represent relatively high pressure).

2.4.4.2. Linear image registration and analysis

Biological data are variable; no two pressure records are identical. To compare pressure records statistically, two approaches can be used. One often-used method requires the selection of landmarks which can then be compared. We choose another method, pedobarographic Statistical Parametric Mapping (pSPM) (Pataky, 2008, Pataky and Goulermas, 2008) that does not require selection of landmarks (which might be difficult between footwear conditions) and performs pixel-level statistics on the entire pressure record. To do this, foot recordings need to be registered so that they show maximal overlap, regardless of the orientation of the foot on the plate, or of the absolute size of the foot. The six records per category (population x condition) were registered within the category (see Pataky et al. (2008b)) and averaged. The averaged records were registered between subjects. Consequently, the shod images were registered to the barefoot ones and averaged, allowing for comparisons between conditions. A detailed guide on the pSPM analysis conducted in this chapter can be found in section "4.3.3.2. Pedobarographic Statistical Parametric Mapping (pSPM)" of this thesis.

We applied this method to the barefoot and indigenously or commercial minimally shod data. This method was also applied to the conventional Western footwear data in the Western data set. However, not enough data was collected for the conventional condition for this analysis method to make conclusive statements. Therefore, we deemed it inappropriate to include in the main body of the paper. These comparisons are available as Appendix A.

2.4.4.3. Foot unroll analysis

A subset of 13 Western subjects had plantar pressure distribution measurements taken in barefoot, minimally shod and 'conventionally' shod conditions (where conventionally shod refers to a wide range of footwear that western populations would typically wear during their daily lives). The data was analysed to investigate variations of *timing* of the foot unroll in the different conditions, in addition to the relative pressure distribution. Because the Centre of Pressure is calculated on the entire footprint, we deem it to be a robust metric that can be compared between conditions, including the conventional Western shod one (even though the latter's pressures, as such, are highly variable).

The previously prepared resampled time series data of the plantar pressure data is a 3D matrix (width x height x time) and was used as the starting point for the foot unroll analysis. This data was linearly interpolated about the temporal axis for 101 frames (i.e., 0 – 100% stance). Each frame was then spatially normalised using the same scaling transformations calculated from the Western 2D peak pressure matrices (linear image registration and analysis section) for each respective print. The prints were grouped into their respective conditions and mean foot unroll timings were calculated for each group. Foot unroll timings are quantified as the displacement of the Centre of Pressure (CoP) from heel to toes along the temporal axis of the registered pressure records. CoP coordinates were calculated, frame by frame, as the weighted average of pressure along the linearly interpolated temporal axis. CoP from each time frame and from each condition were plotted to show the 2D position of the entire foot unroll for each condition (Figure 2.7). Proximal/Distal displacement per frame, and Lateral/Medial displacement were also plotted for the three conditions (Figure 2.8 and Figure 2.9 respectively). We then compared the results of three conditions, pairwise, using one dimensional statistical parametric mapping (1D-SPM) to discover significant variations during the stance phase between any two conditions. 1D-SPM works by detecting field changes in smooth one-dimensional continua (Pataky, 2012). A detailed guide on the CoP analysis conducted in this chapter can be found in section "4.4.3.3 2 Dimensional Centre of Pressure (CoP) using Optimal Scaling Transformations" of this thesis.

2.5. Results

2.5.1. Peak pressure distribution

In general, peak plantar distribution (or relative pressure recordings) between any minimal condition (indigenous or commercial) and barefoot walking were qualitatively similar, and differences did not reach statistical significance. Indeed, even in the shod condition, the heel, hallux, and metatarsal head region can be easily identified whilst wearing indigenous and minimal shoes. The locations of maximal relative pressure seem to correspond well.

2.5.1.1. Indian sample – Kolhapuri footwear

Comparing the full data set for barefoot relative pressure recordings with that for shod (Kolhapuri) walking shows a good correspondence (Figure 2.3). The only visual difference between the two relative pressure recordings is that the region of relatively high pressure about the metatarsal head region is smaller in the shod condition. This is largely due to the additional size of the shoe skewing the perception of the scale. The shod print shows a zone of slight relative pressure distally to the toes due to the presence of a sole that extends beyond the toes. In accordance with the visual correspondence, the pSPM analysis shows no significantly different regions between the two conditions.

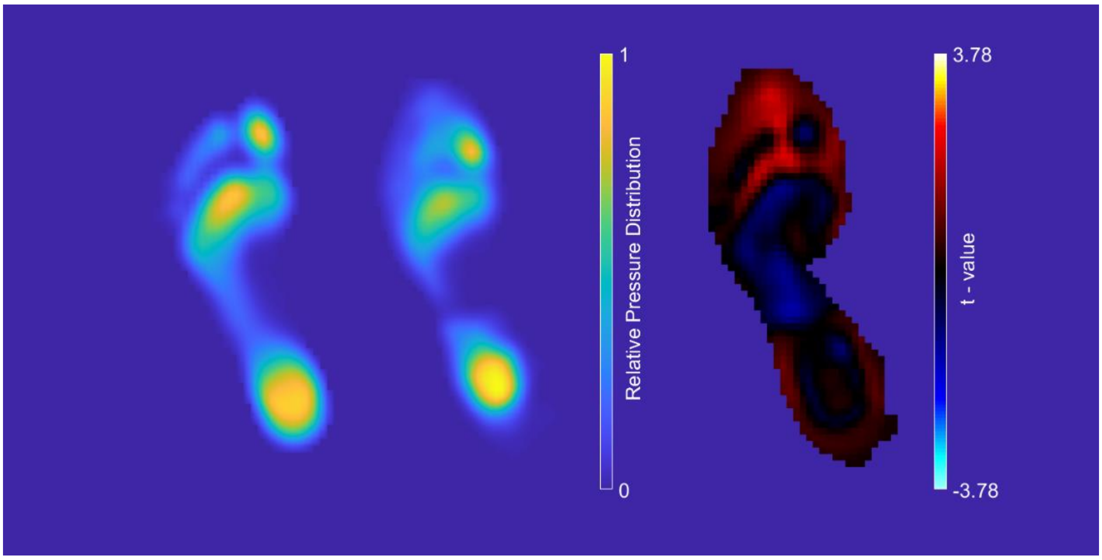

Figure 2.3: Comparison of relative pressures for the Indian sample (34 barefoot participants and 34 shod participants with 195 and 198 trials for barefoot and shod participants respectively). From left to right: Average barefoot pressure; Average shod pressure; Relative pressure distribution colour bar where 0 – 1 refers to zero pressure and to the relative maximum pressures within both the shod and barefoot print; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.

2.5.1.2. Scandinavian sample - reindeer fur boots

Comparing the full data set for barefoot relative pressure recordings with that for shod (reindeer fur boots) walking shows a good correspondence (Figure 2.4). The visual difference between the two relative pressure recordings is that the region of relatively high pressure about the metatarsal head region is smaller in the shod condition. In accordance with the visual correspondence the pSPM analysis shows no significantly different regions between the two conditions.

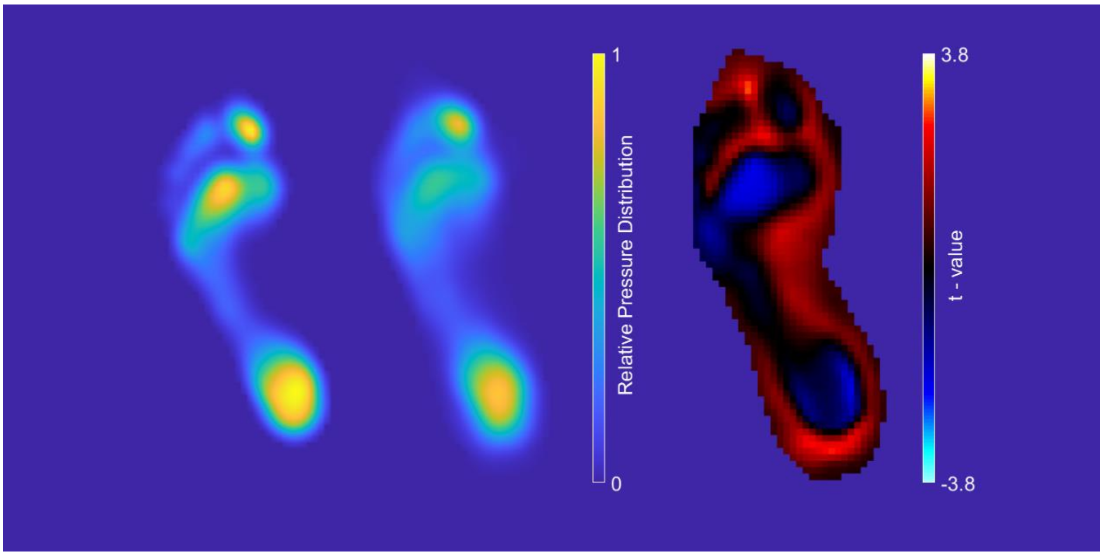

Figure 2.4: Comparison of relative pressures across for the Sami sample (36 barefoot and shod participants with 216 trials for both groups). From left to right: Average barefoot pressure; Average shod pressures; Relative pressure distribution colour bar where 0 – 1 refers to zero pressure and to the relative maximum pressures within both the shod and barefoot print; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.

2.5.1.3. Southern African Sample – n!ang n|osi (eland sandal)

Comparing the full data set for barefoot relative pressure recordings with that for shod (giant eland sandal) walking shows some correspondence (Figure 2.5). The locations of the heel and hallux correspond well between the two trials however the pressure distribution of the metatarsal heads II-III is both proximal and lateral to that in the barefoot condition. In accordance with the visual correspondence the pSPM analysis shows no significantly different regions between the two conditions.

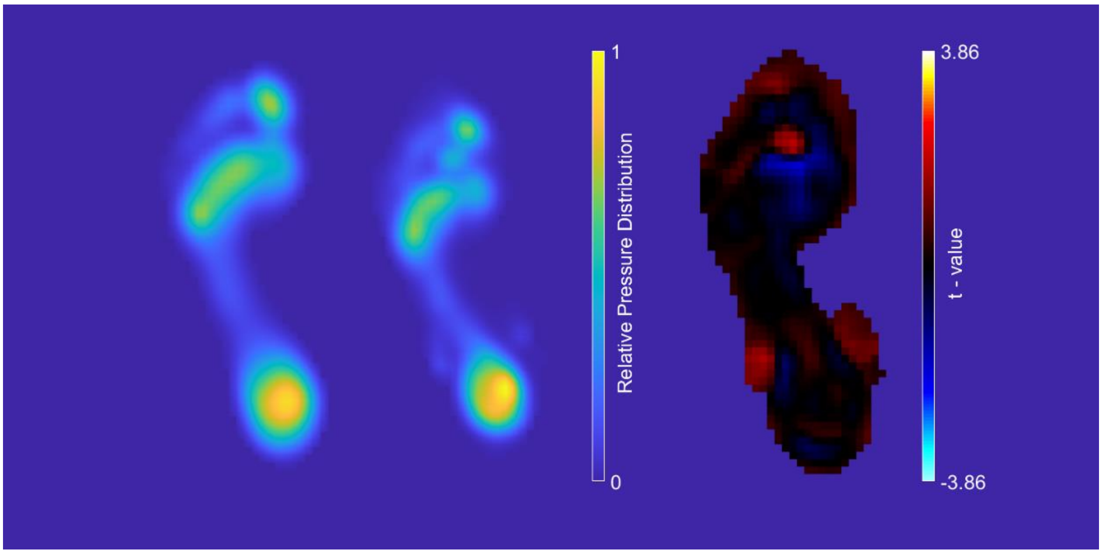

Figure 2.5: Comparison of relative pressures for the Ju'/hoan San sample (33 barefoot participants and 19 shod participants with 199 and 116 trials for barefoot and shod participants respectively). From left to right: Average barefoot pressure; Average shod pressures; Relative pressure distribution colour bar where 0 – 1 refers to zero pressure and to the relative maximum pressures within both the shod and barefoot print; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.

2.5.1.4. Western sample – commercial minimal footwear

Comparing the full data set for barefoot relative pressure recordings with that for minimally shod walking shows a good correspondence (Figure 2.6). However, the toe region in the shod condition appears to be more condensed than the barefoot condition in the lateral-medial plane. This is likely due to the shape of the toe box area of the shoe. In accordance with the visual correspondence the pSPM analysis shows no regions of significance between the two conditions.

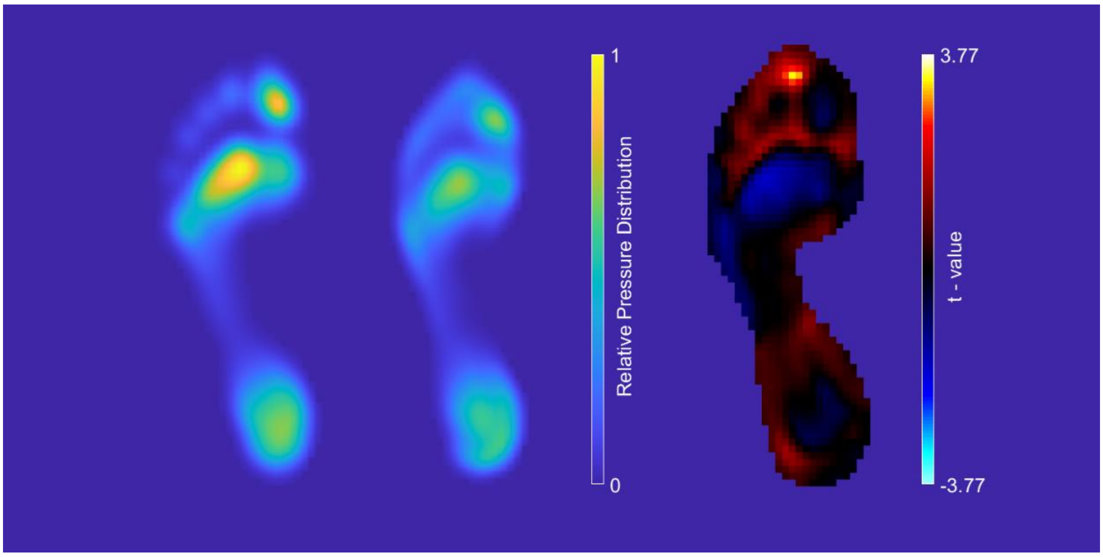

Figure 2.6: Comparison of relative pressures across for the Belgium sample (27 barefoot and shod participants with 163 trials and 162 trials for barefoot and shod groups respectively). From left to right: Average barefoot pressure; Average shod pressures; Relative pressure distribution colour bar where 0 – 1 refers to zero pressure and to the relative maximum pressures within both the shod and barefoot print; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.

We did not involve the conventionally Western shod trials in this population-level quantitative analysis, because of the large variation in footwear types, but within-subject comparisons for all subjects are available in Appendix A. Pressure distribution of conventional Western footwear were very variable and visually different.

2.5.2. Roll-off timing

For the Western European data, Centre of Pressure (CoP) trajectories were compared between three conditions: barefoot, commercial minimal shoes and conventional Western shoes.

The timing of the foot roll-off, as shown by the Centre of Pressure (CoP) did show significant differences between conventional Western footwear and both minimally shod and barefoot walking (Figure 2.8 and Figure 2.9). At initial contact barefoot walking proximal-distal CoP is more distal (4.06 ± 1.11cm, $p<0.05$) when compared to minimally shod walking (2.96 ± 1.1cm) and the conventionally shod condition was not significantly different from the other walking conditions (3.3 ± 2.04cm).

However, significant differences exist between all walking conditions throughout the rest of stance phase.

Here we describe foot unroll along the proximal-to-distal and along the medio-lateral axis.

Proximo-distally, all conditions show a similar overall pattern involving an initial fast progression (0-20% of stance), followed by a slower progression during most of stance, and concluded by a fast progression during push-off (90-100%, see Figure 2.8). Despite their overall similarity, significant differences between the patterns of the three conditions exist.
When the conventionally shod walking condition is compared to the barefoot walking condition, the following significant differences are found. The CoP is more proximal initially (0-20% stance), then more distal (20-60%), thus moving faster early in stance. The clearest difference occurs during push-off (90-100% stance) when the CoP moves more distally.
When minimally shod is compared to barefoot, a similar but less pronounced pattern is observed.
When the two footwear conditions are compared, the only clear difference is from 30-50% of stance, where the conventional shoe has a more distal CoP.
On the whole, barefoot and conventionally shod walking show the greatest differences, with minimally shod walking as an intermediate but more similar to barefoot.

Medio-laterally, again all three conditions show a similar overall pattern. After a brief medial displacement (0-10% stance), the CoP move laterally and keeps doing so until toe-off where a brief medial displacement happens but only when barefoot. Significant differences between the three conditions are only found in mid-stance, where the conventionally shod condition follows a more medial CoP trajectory than the two other conditions (which do not differ between them).

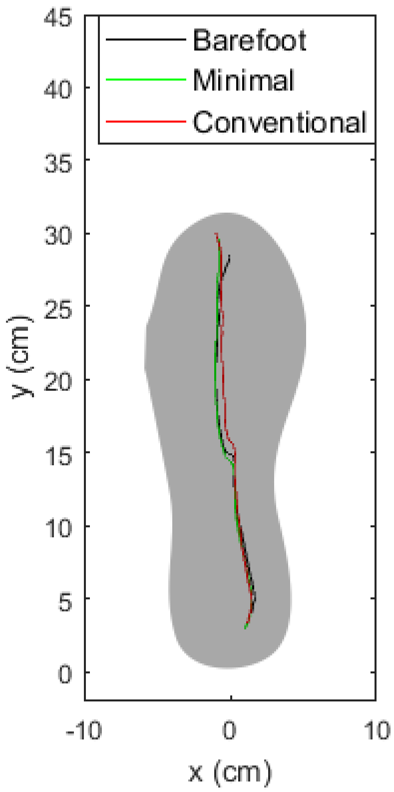

Figure 2.7: Mean CoP trajectories in the x-y plane for the Belgium sample.

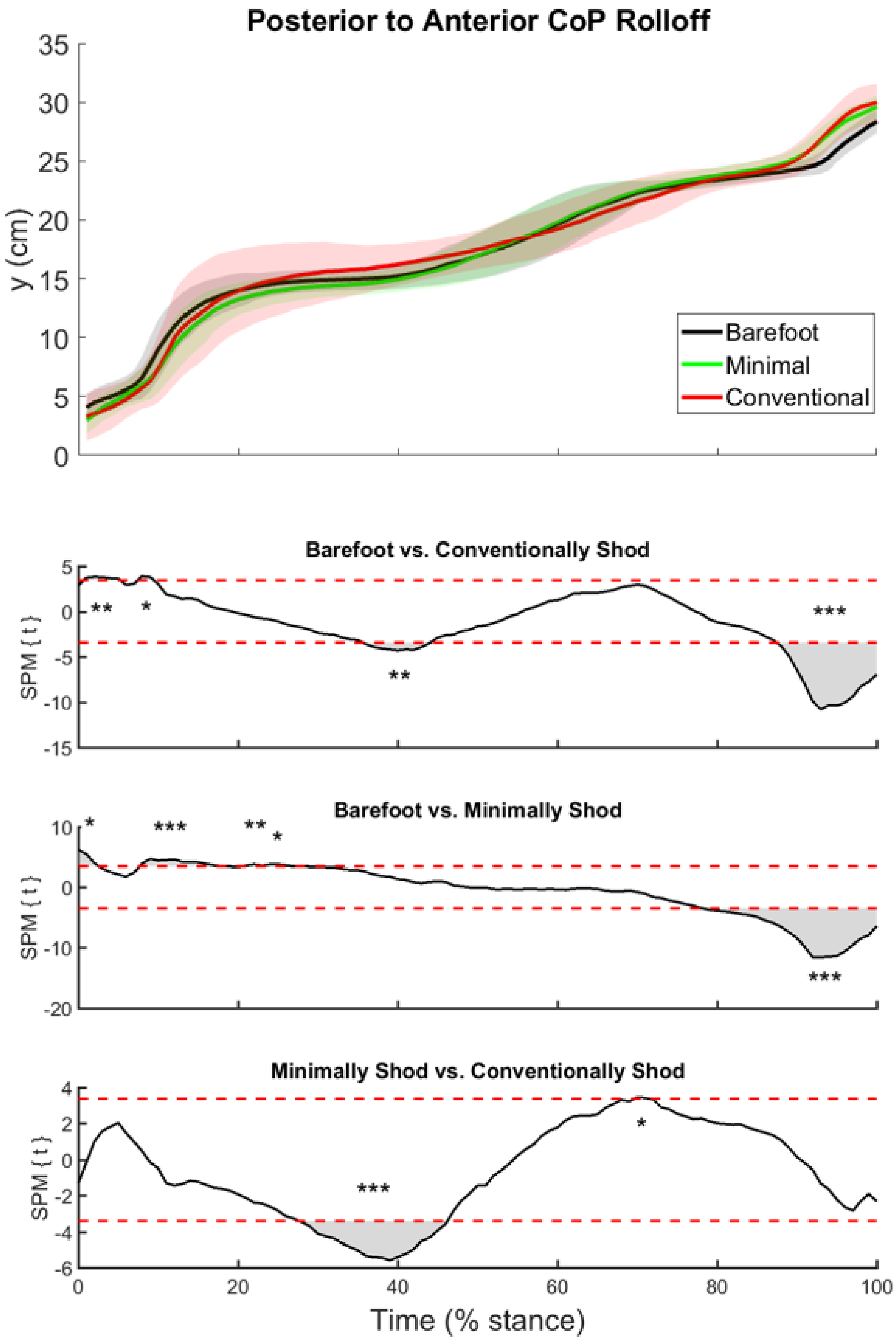

Figure 2.8: Top to Bottom: (1) Posterior to anterior Centre of Pressure (CoP) roll-off from 13 Belgium participants, comparing barefoot, minimally and conventionally shod walking (77, 82, 81 trials respectively). (2 – 4) 1D – SPM, 2 sample t-test with Bonferroni correction showing areas of significant differences between the three possible comparisons. Alpha = 0.02 as derived from the Bonferroni calculation for all 1D – SPM plots; t-critical is shown by the red dotted lines in each plot.

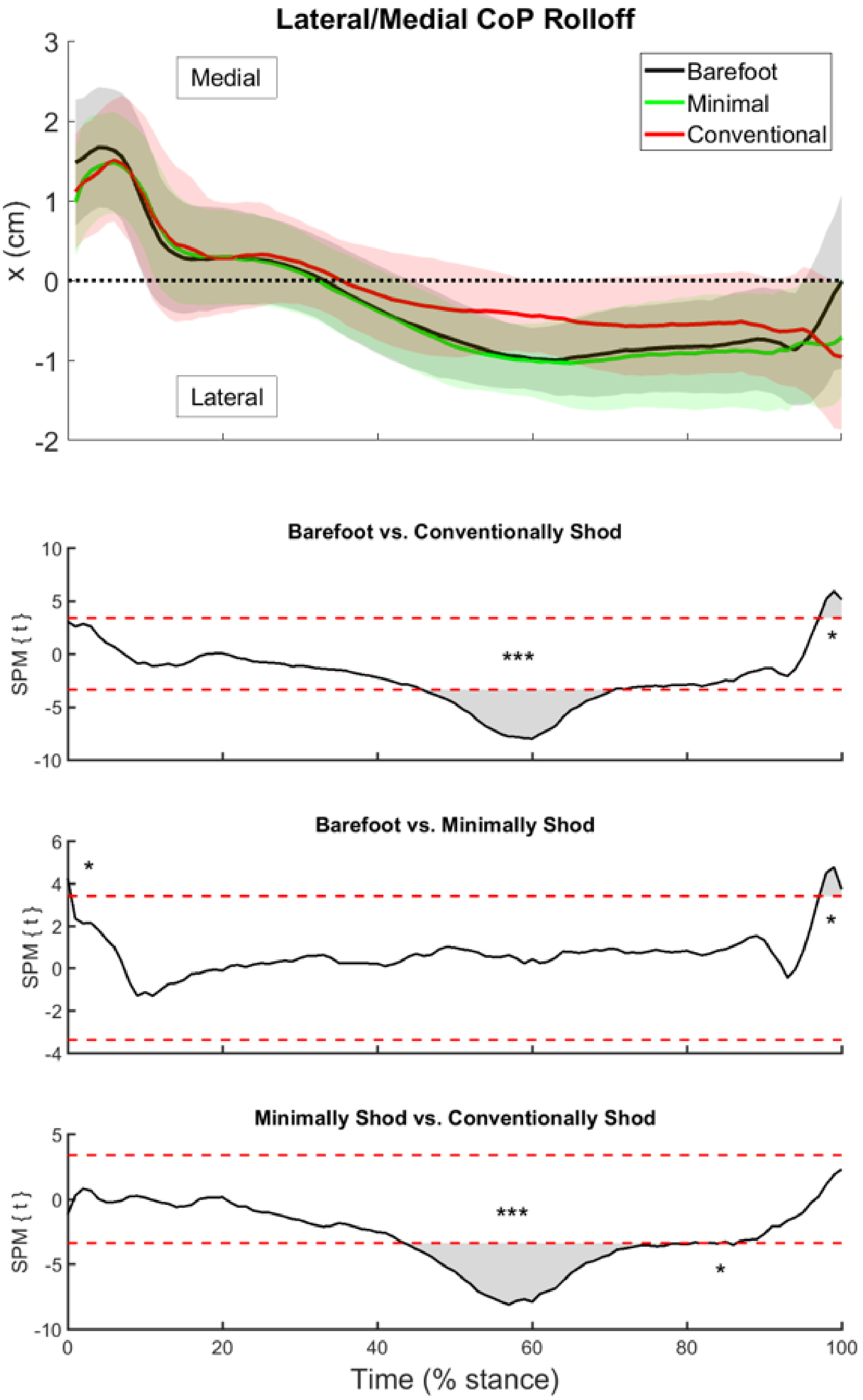

Figure 2.9: Top to Bottom: (1) Medial/Lateral Centre of Pressure (CoP) roll-off from 13 Belgium participants, comparing barefoot, minimally and conventionally shod walking (77, 82, 81 trials respectively). (2 – 4) 1D – SPM, 2 sample t-test with Bonferroni correction showing areas of significant differences between the three possible comparisons. Alpha = 0.02 as derived from the Bonferroni calculation for all 1D – SPM plots; t-critical is shown by the red dotted lines in each plot.

2.6. Discussion

In this study, we addressed two main questions. The first question was whether the relative distribution of peak pressures differs between barefoot and shod walking with indigenous or commercial minimal shoes. The second question was whether there were differences in the timing of unroll between three footwear conditions (barefoot, commercial minimal, conventional Western) within one, Western, population.

2.6.1. Shod versus barefoot walking: within-group comparisons of peak pressure distribution

Visual inspection of the relative peak pressure plots reveals close matches between pressure distributions when barefoot, and when using indigenous footwear as well as commercial 'minimal' footwear (Figure 2.3, Figure 2.4, Figure 2.5 and Figure 2.6). However, the distributions are not identical and there are visual differences between barefoot and shod relative peak pressure plots. These do not show as significant in the pSPM analyses. It should be noted that variation in the data is large, and our sample size is moderate. This might explain the absence of a statistically significant difference, and additional experiments on a larger population might clarify this.

We hypothesised that, since any shoe likely provides some degree of cushioning and increase contact area with the ground, peak pressures in any shod condition would be more spatially distributed (and therefore lower on average) than in barefoot walking.

Visual inspection of the result suggests this is the case in all four populations for the anatomical zones that have the highest relative pressure: the heel, metatarsal (esp. II-III) heads, and the hallux. In contrast, zones that receive low pressures when barefoot, typically show higher pressures when shod. An exception is the midfoot in the Indian sample, which shows a lower peak pressure when shod. This can probably be explained by the presence of a very low heel and stiff outsole in the indigenous shoes, lifting the midfoot off the substrate in many cases. The medial midfoot region is least prone to wear and, therefore, the natural tanned buffalo hide is relatively stiff in that area (Willems et al., 2017).

The combined effect of the general reduction in pressure of high-pressure zones and increased pressure in low-pressure zones is that, as expected, pressures are more equally distributed over a larger area when shod, at least at the level of the shoe-substrate interface.

In the case of the Scandinavian 'Nuvttohat' footwear, it should be mentioned that they are manufactured to perform best on snow and ice, and that this footwear is traditionally used without a sock, but with a padding of so-called 'kinkaheina' grass. We collected data on a hard surface and thus the pressures experienced when walking on snow would probably be even lower than on our pressure plate, or on ice. This is because snow will dissipate the load experienced during walking of the over a greater period of time resulting lower peak pressure values.

Interestingly, the subtle pattern of more uniform peak pressures, seen in indigenously or minimally shod conditions, bears resemblance to a similar pattern of more uniform peak pressures in habitually barefoot South Indians when compared to habitually shod (but barefoot walking in the experiments) peers (D'Août et al., 2009). It could be questioned whether there might be a mechanical explanation for this similarity, i.e. do habitual barefoot walkers have a thicker foot sole functioning in a similar fashion to the very thin leather soles seen in our indigenous footwear, or to the thin rubber sole of commercial minimal shoes? A recent study on foot calluses in barefoot and shod walkers suggests this might be the case (Holowka et al., 2019).

It should be stressed that plantar pressure recordings, while providing crucial information on the interface between the walking humans and their mechanical environment, do not provide a full picture of the complexity of walking, and differences between shod and barefoot walking have been well established by kinematics and kinetics (e.g. a variety of Western footwear, (Zhang et al., 2013); flip-flops, (Chard et al., 2012, Chard et al., 2013); indigenous footwear, (Willems et al., 2017). Walking barefoot, compared to shod walking proved to yield slightly higher impact accelerations, at least on a hard substrate (Willems et al., 2017).

2.6.2. Roll-off timing

Our second hypothesis was that the temporal pattern of foot unroll in minimal footwear would be more similar to that of barefoot walking, than is the case for conventionally shod walking. Temporal analysis of the Western sample, comparing barefoot with minimally and conventionally shod conditions, suggests that this is partially true. The indigenous or minimal footwear exhibits some temporal patterns similar to the barefoot condition, but also some patterns similar to conventionally shod walking for both proximal/distal and lateral/medial analysis (Figure 2.8 and Figure 2.9). Greater differences between minimally shod walking and conventionally shod walking may have emerged if a standardised western shoe had been used by all the participants. The decision was made to test participants in their daily footwear as western conventional footwear is very variable in a conventionally western shod community so results from a standardised conventional western shoe would not be as meaningful.

Overall, indigenous or minimal footwear is a mid-point between walking barefoot and walking conventionally shod. This finding is in keeping with the systematic literature review comparing the current work on barefoot and conventionally shod walking (Franklin et al., 2015).

2.6.3. Methodological challenges

The Indian, Namibian and Scandinavian data for this study were collected in rural settings, by bringing in equipment and setting up a temporal 'gait laboratory'. While this approach has been necessary, and fruitful, to collect the unique data of indigenously shod populations, it does limit technical possibilities. For example, two standard pieces of equipment of a conventional gait lab, force plates and a 3D motion-capture system, could not be used. A plantar pressure plate is portable and has been successfully used to study walking in field settings before (D'Août et al., 2009, Stolwijk et al., 2013).

The use of plantar pressure plates has been well established and poses few technical issues. While the magnitudes of the recorded pressures might not be as accurate as the forces recorded by a force plate, results from pressure plates provide a good overview of relative pressure distribution and are reliable, even between manufacturers (see Hafer et al. (2013)). The main challenge with the use of footwear on a pressure plate is: how do these pressures relate to the pressures experienced by the foot? The limited literature on shod walking medial/lateral CoP exhibits lateral CoP at heel strike (Zhang et al., 2017), however shod walking CoP in the present study is medial at heel strike. This is likely because the present study used a pressure mat that records the CoP of the shoe sole whereas Zhang et al. (2017) uses pressure sensitive insoles that recorded the CoP of the sole of the foot while shod. To prove these differences are caused by differences in measuring equipment and potentially find other plantar differences between insole and pressure mat shod walking a simultaneous recording of pressure data using a pressure plate and an insole system should be conducted. For overviews of the use of pressure plates and insoles, see e.g. Giacomozzi et al. (2012), Abdul Razak et al. (2012), Barnett et al. (2001), Low and Dixon (2010).

Few studies have addressed shod locomotion, running, on a pressure plate but they have focused on CoP displacement and not on a complete spatial analysis of the pressures themselves (e.g., Dixon and McNally (2008), Greenhalgh et al. (2014)). In the case of our indigenous footwear and commercial minimal shoes, however, the correspondence between shod and barefoot prints is striking, and even shod prints reveal a good degree of anatomical detail such as a clearly defined hallux. We hypothesise that the pressures as measured by the plate correlate closely to what the foot experiences. It should be noted that all soles (except for the conventional Western shoes) are only a few mm thick, relatively hard but flexible.

The use of pressure sensitive insoles would allow for a direct measurement of foot pressures, and this has indeed extensively been used in non-minimal footwear, where a good correspondence between plate pressures and plantar pressures cannot be assumed. However, the use of pressure insoles would be a challenge in the barefoot condition and would require some form of gluing or use of a sock (e.g. Burnfield et al. (2004)), potentially affecting results. The use of insoles in the shod condition and of a plate in the barefoot condition is not preferable if a direct comparison (as in this study), without technical confounding factors, is to be made.

The use of pixel-based pSPM instead of zone-based analyses has been shown to give valid and objective results without prior anatomical assumptions (e.g., Bates et al. (2013), Pataky et al. (2008a), Pataky and Goulermas (2008)). Image registration between different shaped and sized plots (e.g. barefoot versus shod) is not unequivocal, and although non-linear registration (Pataky et al., 2011) is a suitable solution for plots made by comparable morphologies, in the future it would be worth exploring to what extent registration might impact the results between barefoot and shod prints.

Based on plantar pressure recordings, we conclude that Kolhapuri footwear, Nuvttohat footwear, N!ang nIosi footwear, and commercial minimal shoes, can all be considered 'minimal footwear'.

When comparing Western conventional footwear with minimal footwear and barefoot walking, there are subtle but significant differences regarding temporal patterns.

2.7. Acknowledgements

We greatly appreciate the collaboration of all participants in this study from India, Finland, Namibia and Belgium. Special thanks go to the artisan community of Toehold in India, Sogsakk in Finland, the San Community in Namibia and the M2Ocean lab of the University of Antwerp for facilitating all logistics.

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2.8. Declaration of Interest

A full set of Vivobarefoot 'The One' minimal shoes was donated to Catherine Willems by Vivobarefoot, London, UK.

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3. Chapter 3: Daily Activity in Minimal Footwear Increases Foot Strength

3.1. Chapter 3 Covering page

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3.1.2. Author Contributions

Rory Curtis: Conceived, designed (including design and organizing manufacture of the MPJ.STAR) and carried out the study, wrote the chapter, and edited the chapter.

Catherine Willems: Helped with the collection of results from the Southern African Ju|'hoan San sub-group (HBM), supervised and guided chapter write up.

Paolo Paoletti: Supervised and oversaw the programming of the MPJ.STAR.

Kristiaan D'Août: Provided supervision and guidance for all aspects of the project and chapter.

3.1.3. Chapter 3 Foreword

This chapter evaluates the influence of regularly walking in minimal footwear on foot strength and foot morphology as this thesis' introduction literature review revealed that regular running in minimal footwear increases foot strength but, at the time of this chapter's conception, no literature had investigated the influence of walking in minimal footwear on foot strength. This chapter evaluated foot strength and morphology of the MFA (Minimal Footwear Adaption) group pre and post intervention period in order to answer an aspect of the foot function aspect of the second research question: Can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function? In addition to this, EMS and HBM group foot strength and morphology was evaluated. These two groups provided additional time points of footwear wearing history so that further insight could be obtained beyond six months of regular footwear use. These groups were added given that the findings of chapter 2 suggested regular use of minimal footwear had long-term effects. The results from these two groups also went towards answering the third research question: What are the long-term effects of walking in minimal footwear? This chapter also investigated the spatial and mechanical properties of both minimal and conventional footwear. Overall, this chapter evaluated the following hypotheses:

- Six months of regular minimal footwear use increases foot width.
- Foot strength increases in conventionally western shod populations after using minimal footwear for daily activity after a six month period.
- Foot strength continues to increase in conventionally western shod populations if regular use of minimal footwear is maintained after a six month period.
- Conventionally western shod adults will have comparable foot strengths to habitually barefoot and/or minimally shod adults given sufficient minimally shod walking experience.
- Experienced minimally shod walkers will have greater foot width than minimally shod walkers.

It should also be noted that the HBM group in a San sub-group that had some participant overlap with the San group from the indigenous footwear study but should ultimately be considered as a separate group.

3.2. Abstract

The human foot is highly specialised for efficient bipedal locomotion. The longitudinal arch of the foot has the ability to both stiffen and deform during gait, allowing it to be a compliant shock absorber during impact and an efficient

propulsive lever during push off. Intrinsic foot muscles aid this deformation, making them important for good foot function. Regular activity in minimal footwear is theorisied to improve intrinsic foot muscle strength and therefore could be beneficial to musculoskeletal health.

This study investigated the influence daily activity in minimal footwear has on foot strength and foot morphology. Habitually conventionally western shod adults were recruited to wear minimal footwear for a six-month intervention period. Foot strength (evaluated as maximum isometric plantarflexion strength of the toes about the metatarsophalangeal joint (MPJ)) was measured in pre and post intervention period tests. Key biometrics including foot metrics were also measured in both tests. This group was the minimal footwear adaption (MFA) group. Two additional groups were investigated to add further insight on the long-term influence of minimal footwear on foot strength and foot morphology: One group of previously habitually conventionally western shod healthy adults with 2.5 ± 2.4yrs experience in minimal footwear (EMS). The second additional group; a population of habitually barefoot and/or minimally shod healthy adults (HBM). Both EMS and HBM groups had foot strength and key biometrics evaluated.

This study showed foot strength increased by 57.4% ($p<0.001$) after six months of daily activity in minimal footwear. Both EMS and HBM groups had similar foot strength as the MFA group, suggesting six months of regular minimal footwear use is a sufficient time period for habitually conventionally western shod adults to return to naturally strong feet.

3.3. Introduction

The human foot forms the body's contact with the ground. Forces produced by the muscles of the lower limb are transmitted to the ground via the foot to generate forward propulsion in addition to supporting body weight (Crompton et al., 2010). The human foot has evolved a number of unique anatomical adaptations to support effective bipedal locomotion. Well-defined longitudinal arches had evolved by around 2 million years ago, found in early *Homo erectus* (Bennett et al., 2009). An adaptation which helps prevent mid-tarsal break, that is often observed in the feet of apes (Susman et al., 1984). The springy plantar aponeurosis present in modern day *Homo sapiens* reduces the cost of transport by cyclically storing and releasing energy during locomotion (Ker et al., 1987, Stearne et al., 2016, Erdemir et al., 2004). It is also a key component to the windlass mechanism (Hicks, 1954) which contributes to the foot's ability to be an effective shock absorber on impact and an efficiently stiff force transmitter at push-off (Griffin et al., 2013). An ability which is absent from facultative bipeds such as apes (Griffin et al., 2010). *Homo sapiens* also have considerable intrinsic foot musculature. The intrinsic foot muscles aid longitudinal arch deformation control (Kelly et al., 2014) and help stabilise the foot and improve balance during stance phase (McKeon et al., 2015).

Studies have shown intrinsic foot muscles to actively influence longitudinal arch stiffness (Kelly et al., 2015, Kelly et al., 2014, Fiolkowski et al., 2003, Headlee et al., 2008, Mulligan and Cook, 2013) in addition to the passive role of the plantar aponeurosis. Two of these studies specified the Abductor Hallucis, Flexor Digitorum Brevis, and Quadratus Plantae muscles to influence longitudinal arch control (Kelly et al., 2014, Kelly et al., 2015). In addition to this, the intrinsic foot muscles have been shown to assist in the compression and recoil of the longitudinal arch (Kelly et al., 2015, McKeon et al., 2015). Therefore strong intrinsic foot muscles improve the longitudinal arch deforming mechanism, beneficial to an efficient gait.

Increasing intrinsic foot muscle strength has been shown to positively influence balance and stability, and reduce fall risk in older people (Spink et al., 2011). Conversely, weak feet have been shown to be a factor in fall risk (Mickle et al., 2008). Weak intrinsic foot muscles have also been associated with foot injury and deformities (Allen and Gross, 2003, Garth JR and Miller, 1989, Cheung et al., 2016, McClinton et al., 2016, Kamonseki et al., 2016) such as hallux valgus (Soysa et al., 2012), claw toe and hammer toe (Myerson and Shereff, 1989). Given that strong intrinsic foot muscles improve stability and reduce foot deformities, strong intrinsic foot muscles are desirable over weak ones.

Foot muscle strengthening exercises are an effective way to strengthen the intrinsic muscles of the foot. Foot doming is an exercise that is commonly employed by clinicians to strengthen the foot, with much success (Ridge et al., 2017). Another method of foot strengthening might be using minimal footwear. Where minimal footwear is defined as "Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices" (Sinclair et al., 2013).

Studies have shown foot strength can be increased by performing sports in minimal footwear for healthy adults (Miller et al., 2014, Goldmann et al., 2013a, Chen et al., 2016, Johnson et al., 2016). However, this can also lead to injury if done excessively (Ridge et al., 2013). Walking in minimal footwear during daily activities, rather than performing sports, might have a lower injury risk but we hypothesise that it will also increase foot strength. Ridge et al. (2019) found runners walking in minimal footwear for eight weeks increased their foot muscle strength. Holowka et al. (2018) found the intrinsic foot muscles; Abductor Hallucis and Abductor Digiti Minimi to be relatively larger in a habitually minimally shod population when compared to a habitually conventionally western shod population – providing further evidence that walking in minimal footwear increases foot strength.

Ridge et al. (2019) and Holowka et al. (2018) have shown regular use of minimal footwear increases intrinsic foot muscle strength. Cross-population comparisons always have limitations and the findings from the work by Holowka et al. (2018) can be skewed by other differences between the populations, for example, activity. The work by Ridge et al. (2019) is an eight-week prospective cohort study, where walking in minimal footwear throughout the intervention period is the only variable. This ultimately proves walking in minimal footwear increases foot strength. However, it would be interesting to see if these effects continue over the 8-week intervention time period, and it is currently unknown how much time of regular minimally shod walking it would take for conventionally western shod adults to exhibit foot strength comparable to habitually barefoot and or minimally shod adults. To gain as much insight into the timescale the influence of regular minimal footwear use has on foot strength, the present study will investigate several groups with varying experience in minimal footwear use, including one prospective group.

In addition to this, experience in minimal footwear may also influence foot morphology. Habitually minimally shod participants have been found to have significantly higher longitudinal arches than conventionally western shod participants (Lieberman, 2014). This agrees with a study by Hollander et al. (2017a) who discovered significantly higher static arch heights in habitually barefoot children between the ages of six and 18 years when compared to conventionally shod children. Whereas another study conducted by D'Août et al. (2009) found no differences between static longitudinal arch heights of habitually barefoot and minimally shod Indians when compared to conventionally western shod Europeans. However, most researchers agree that habitually barefoot and/or minimally shod populations have wider feet (Ashizawa et al., 1997, Hollander et al., 2017b, D'Août et al., 2009). It can be seen from the literature that minimal footwear may have an influence on biometrics as well as foot strength. Yet no study has attempted to investigate the long-term impact on foot biometrics for conventionally western shod adults transitioning to minimal footwear. As a result, this study will investigate long-term minimal footwear influence on foot biometrics as well as foot strength on habitually conventionally western shod healthy adults.

This study has two central aims. The first; to discover the influence six months of regular minimal footwear use has on foot strength and biometrics, for adults that were previously habitually conventionally western shod. The second; to determine how much regular minimally shod walking experience it would take for conventionally western shod adults to exhibit foot strengths and biometrics comparable to habitually barefoot and or minimally shod adults (or if they would at all). In response to the aims, we hypothesise the following:

1. Foot width increases in conventionally western shod populations after using minimal footwear for daily activity after a six month period.

2. Foot strength increases in conventionally western shod populations after using minimal footwear for daily activity after a six month period.
3. Foot strength continues to increase in conventionally western shod populations if regular use of minimal footwear is maintained after a six month period.
4. Conventionally western shod adults will have comparable foot strengths to habitually barefoot and/or minimally shod adults given sufficient minimally shod walking experience.

3.4. Methods

The present study combines both prospective study design and cross-population study design to gain greater insight into the influence regular minimally shod walking has on habitually conventionally western shod adults. The study investigates the influence six months of daily activity in minimal footwear has on foot strength and biometrics, for adults that were previously habitually conventionally western shod. For the purposes of reference this study is referred to as the minimal footwear adaption (MFA) study. This study also goes on to compare the findings from the MFA study to two additional groups: One group of previously habitually conventionally western shod adults with 2.5 ± 2.4yrs experience in minimal footwear (EMS). The second additional group; a population of habitually barefoot and/or minimally shod adults (HBM). Both EMS and HBM groups had foot strength and key biometrics evaluated.

3.4.1. Minimal Footwear Adaption (MFA) Study

Habitually conventionally western shod participants transitioned from exclusively conventional footwear use to predominantly minimal footwear use for a six month intervention period (MFA – intervention sub-group, n = 22, 13 male, 9 female, 26.7 ± 6yrs, 24.4 ± 2.7 BMI). Additional habitually conventionally western shod control participants continued to wear conventional footwear throughout the six month intervention period (MFA – control sub-group, n = 24, 14 male, 10 female, 28.4 ± 7.4yrs, 22.8 ± 3.1 BMI). All MFA participants had biometrics (Table 3.1) and foot strength evaluated in pre and post intervention period tests. MFA participants self-selected sub-groups for feasibility purposes however both intervention and control sub-group biometrics and foot strength matched, pre-intervention period.

The intervention participants were allocated minimal footwear (Vivobarefoot Stealth II shoes (Figure 3.1)) to wear for the intervention period. MFA – intervention participants were required to wear the minimal footwear for a minimum of 70% of the time they were shod, as well as at least six day a week, and control participants followed the same time constraints for their most frequently worn conventional footwear. In addition to this, intervention participants were informed of the risks of running in minimal footwear and were instructed not to run or exercise in them.

MFA participants were only recruited if they met the following inclusion criteria: free from lower limb pathologies for a minimum of six months prior to the start of the study, aged between 18 – 55yrs, had a BMI within the range of 18.5 – 30, and had never worn minimal footwear before.

All MFA participants filled out a weekly participant activity log throughout the intervention period to monitor activity and footwear wearing patterns. This was also used as the platform to communicate any discomfort experienced with each participant's footwear. All MFA participants finished the study ± one week within the six-month intervention period, with the exception of one, who finished 12 days after the intended end date. Five participants dropped out due to injury (unrelated to the study) or failure to keep up with the study requirements, these participants are not reported within this study.


Figure 3.1: Lateral Views of the minimal footwear used for the minimal footwear adaption study (Vivobarefoot Stealth II trainers). Image sources from Vivobarefoot (Vivobarefoot, 2017).

All data for the MFA study was collected in the Gait Lab at the University of Liverpool under ethics granted by the University of Liverpool Health and Life Sciences Research Ethics Committee (Human participants, tissues and databases), reference number 1911. At the start of the study, MFA participants came into Gait Lab and would fill out an activity, health and footwear habits questionnaire (Future Footwear Questionnaire). The future footwear questionnaire can be found in Appendix C. They would then change into non-restrictive clothing and have key biometrics recorded. Firstly, mass was recorded with SecaI360 Wireless scale (e = 0.05kg), followed by height using the height measuring capabilities of the scale. Foot length was recorded using a metal ruler that the participant would place his/her right foot on. The participant would stand up straight with feet a shoulder width apart. At which point distance between the most posterior point of the heel to the most distal point of the most distal toe (either the hallux or the 2nd toe) would be recorded. Foot width was recorded from the 1st metatarsal to 5th metatarsal heads using a digital outside calliper (e = 0.1mm). Toe length was measured as the length of the hallux, from the first MPJ to the most distal part of the hallux. Navicular height (our chosen measure for static arch height), measured from the navicular tuberosity to the ground using a tape measure. Leg length was measured from the greater trochanter to the ground by using a tape measure. Only one measurement per participant was taken for each metric. The same biometrics at the start of the study were recorded when participants came in for their post-intervention tests, following the same procedure. MFA intervention and control participant biometrics pre and post intervention can be seen in Table 3.1. Additionally, all MFA participants biometrics measured before the intervention period can be seen in Table 3.2.

Prior to the participant's arrival, MFA participants were instructed to bring the footwear they most regularly wore for the initial Gait Lab study. The brand, name and shoe size of each participant's footwear were recorded. The regular footwear was then weighed using OHaus Scout weighing scales (e = 0.1g). Shoe length was recorded as the linear distance from the very back of the footwear's heel to its most distal end of the footwear. Shoe width was recorded as the linear distance from each end of the widest point of the footwear sole (using a digital outside calliper). Sole thickness was recorded as the sole thickness from the central part of the heel section to the base of the sole by using the outside callipers. Stack height was calculated as shown in equation one.

$$stack\ height = \ sole\ thickness - (toe\ box\ thickness - upper\ thickness) \qquad (1)$$

Where toe box thickness was measured as the thickness of the sole of the centre toe box area as well as the upper thickness above it, when the upper material was pushed down to be in contact with the insole. Upper thickness was measured as the upper material thickness directly above the centre of the toe box area using the outside callipers. The right shoe of each MFA participants regular footwear was then placed in a specialised jig fitted to a Lloyd LRX worm drive material property tester. Tests were performed to measure the footwear's bending stiffness about the MPJ region and its sole hardness.

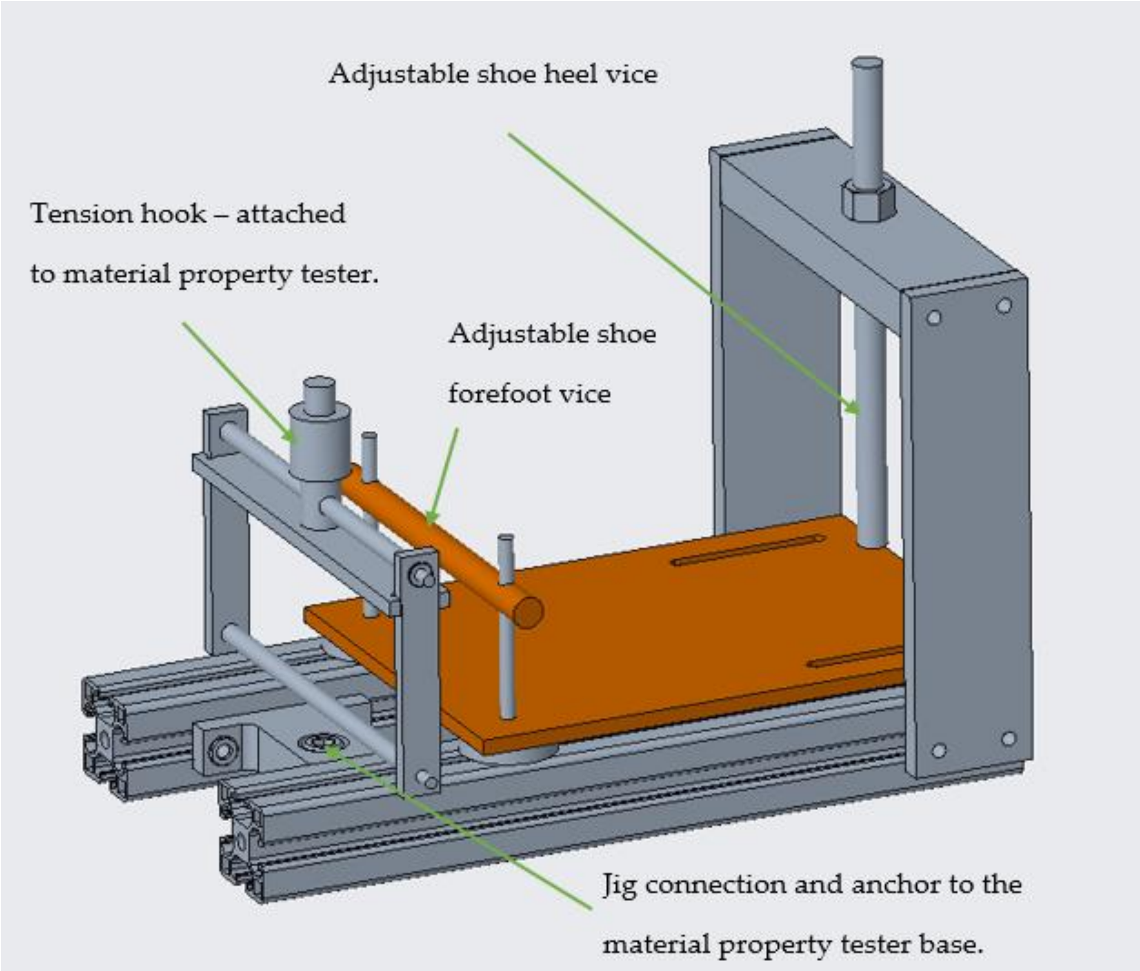

Figure 3.2: Annotated representation of the specialised jig used for footwear bending stiffness and sole hardness testing.

Figure 3.2 shows the jig set-up for bending stiffness testing. Participant footwear was placed into the jig and its position secured with the two adjustable vices, taking care to place the adjustable shoe forefoot vice over the region of footwear that surrounds the MPJ. The tension hook would raise at 500mm/min until the shoe forefoot reached an angle of 25 degrees, at which point the bending stiffness was recorded. The tension hook is then swapped out for a 57mm spherical indenter and adjustable vices repositioned to test the sole hardness at the heel. Taking a measurement for sole hardness proved more challenging as the Lloyd LRX worm drive material property tester would not allow for compressive loads greater than 50N. To make the most of the limited load range, maximum sole compression displacement was recorded at the 50N limit. This meant that sole hardness within this study is measured as displacement per unit load (mm/N) as opposed to the conventional load per unit displacement (N/mm). Therefore, this study does not measure sole hardness, but rather sole softness, and will report it as such.

The spatial and mechanical properties of the minimal footwear were also measured following the same procedure. A men's 41 EU Vivobarefoot Stealth II shoe was used to take the footwear properties from, given that the average foot length of the MFA participants was 252mm. The minimal footwear's spatial properties were measured once and mechanical properties were measured five times, and the average was taken. Footwear properties were not measured post-intervention. The resultant footwear properties can be seen in Table 3.4.

Finally, participants had foot strength evaluated. Foot strength was evaluated, using a modified version of a technique employed and validated by Goldmann et al. (Goldmann and Brüggemann, 2012, Goldmann et al., 2013a, Goldmann et al., 2013b). This method quantifies foot strength as the maximum isometric plantar flexion strength of the toes about the metatarsophalangeal joint (MPJ). For the purposes of this study this measure of foot strength will be referred to as Toe Flexion Strength (TFS). In order to measure TFS, a custom dynamometer was built and is known as the Metatarsophalangeal Joint Strength Tester And Recorder (MPJ.STAR). The MPJ.STAR recorded the moment (N.m) generated by TFS at sample frequency of 4.9Hz and accuracy of ±0.1N.m. The MPJ.STAR was designed using the Pahl and Beitz design process (Pahl and Beitz, 2013). During this study the load plate of the device was angled to 25°. 25° was chosen as Goldmann et al. (2013a) found this angle to be successful in showing changes in TFS before and after exercising in minimal footwear. Participants were instructed to sit on an adjustable chair with the back straight and flush with the back rest of the chair. Their right naked foot was then placed onto the MPJ.STAR, taking special care to correctly position the metatarsophalangeal joint at the device's plate division so that the hallux and lessor toes rested on the angled load plate (Figure 3.3). The participant's position was adjusted until the investigator was satisfied that the participant's knee and ankle angle were both at 90° upon visual inspection of the lateral side. The participant was instructed to push as hard as they could with their toes onto the load plate while making sure to keep their heel on the base plate. They were instructed to keep their back straight, taking care not to lean back into the back rest of the seat, for additional leverage (Figure 3.4). Participants were given as many attempts as were required until the investigator was satisfied with the exertion and the participants felt comfortable and confident they could reliably repeat the motion. Participants were given a minimum of one minute rest after the practice trials before going into the test. Participants completed five trials each lasting 10 seconds with a one-minute rest between trials.

Figure 3.3: Image depicting correct foot position on the custom-made dynamometer (MPJ.STAR).

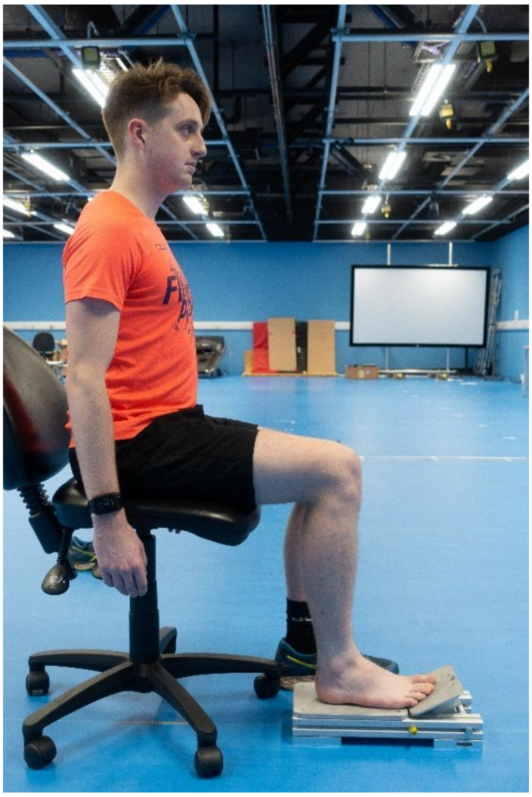

Figure 3.4: Image depicting the correct position before using the custom-made dynamometer (MPJ.STAR).

3.4.2. Experienced Minimally Shod (EMS) Group

Experienced minimally shod walkers from a habitually conventionally western shod background (EMS group; n = 20, 10 female, 10 male, 31.1 ± 6.7yrs, 22.8 ± 2.7BMI) were recruited if they have been using minimal footwear as their most frequently worn footwear for at least six months prior to starting the study. All EMS participants were recruited from the UK. All data collected from EMS participants was done outside of the Gait Lab using a modified methodology to that of the MFA group. All data for the EMS study was collected under ethics granted by the University of Liverpool Health and Life Sciences Research Ethics Committee (Human participants, tissues and databases), reference number 1911. EMS participants had their biometrics (Table 3.1), footwear properties (Table 3.4) and TFS recorded using the same methods employed on the MFA group. The material properties of the EMS group footwear were not recorded. EMS participants filled out the future footwear questionnaire and indicated how long they had been regularly wearing minimal footwear for. Data from EMS participants was only collected once.

3.4.3. Habitually barefoot and/or minimally shod (HBM) Group

Habitually barefoot and/or minimally shod walkers (HBM group; n = 15 11 male, female, 32.2 ± 9.7yrs, 20 ± 4.1BMI) were recruited and studied in the field. All participants were recruited were Ju|'hoan San heritage from the Nyae-Nyae Concession Area, Otjizondjupa region. All data for the HBM study was collected approved by the University of Antwerp Ethics Committee; ethics number: B300201112278. The HBM group had their foot strength and biometrics (Table 3.2) recorded in the same way as the MFA and EMS groups. Except for foot length and width which were not recorded. Footwear properties of the HBM group were not recorded.

3.4.4. Analysis

3.4.4.1. Biometrics

Participant biometrics were recorded and stored in an excel database. This data was imported into Matlab2017a for statistical analysis. One way ANOVA was performed to determine statistically significant differences between control and intervention participants pre and post intervention period. No significant differences between the sub-groups were identified therefore no follow up post-hoc test was conducted. One way ANOVA was also performed to determine statistically significant biometric differences between all MFA participants pre-intervention period, EMS participants and HBM participants. p-values were then calculated using the appropriate post-hoc test via standard syntax built-in Matlab.

3.4.4.2. Footwear Properties

MFA and EMS participant footwear properties were recorded and stored in an excel database. This data was imported into Matlab2017a for statistical analysis. One-way ANOVA was performed to determine statistically significant spatial and material property differences between the Vivobarefoot Stealth II trainers given to the MFA intervention participants (Min), the 'conventional' footwear worn by all MFA participants, pre-intervention period (MFA), and the footwear worn by the EMS participants on the day of testing (EMS). p-values were then calculated using the appropriate post-hoc test via standard syntax built-in MATLAB.

3.4.4.3. Participant History

MFA and EMS participant history was recorded and stored in an excel database. This data was imported into Matlab2017a for statistical analysis. Un-paired t-tests were used to discover any statistically significant differences between the MFA and EMS participant history.

3.4.4.4. Toe Flexion Strength

The MPJ.STAR recorded the moment (N.m) generated by TFS at sample frequency of 4.9Hz and saved the result of each trail to a text file. The text files were imported into Matlab2017a. The data was then smoothed with a low-pass 2nd order 1Hz Butterworth filter. The maximum moment was taken from each trail and the average maximum moment was derived for each participant.

For the MFA study, change in TFS was calculated as the percentage change in post intervention TFS compared to the baseline, as shown in equation 2:

$$Change\ in\ TFS = \frac{TFS_{post} - TFS_{pre}}{TFS_{pre}} \times 100 \qquad (2)$$

Both the control and intervention groups had non-uniform distribution in change in TFS. Therefore, significant differences were found with one-sample Wilcoxon signed ranked tests.

For a cross-population comparisons, TFS was normalised to body mass. TFS per unit mass for each population had non-uniform distribution. Significant differences were found with the Krustal Wallis test.

3.5. Results

3.5.1. Biometrics

MFA control and intervention sub-group biometrics pre and post intervention period are shown in Table 3.1. No significant differences were found in any of the recorded biometrics before and after the intervention period in both the control and intervention groups.

Table 3.1: Biometrics and activity patterns of the MFA group pre (pre) and post (post) intervention period. Spilt into control and intervention sub-groups. "Reported weekly activity" and "weekly footwear use" range over both pre and post intervention columns as these characteristics were taken during the six-month intervention period. No statistically significant differences were found between any of the groups.

Biometric or Activity	Control (n = 24)		Intervention (n = 22)	
	Pre	Post	Pre	Post
Age (yrs)	28.4 ± 7.5	28.9 ± 7.5	26.7 ± 6.2	27.3 ± 6.2
Mass (kg)	67.7 ± 11.9	67.6 ± 11.5	73.2 ± 12.8	73.1 ± 11.8
Height (cm)	172.2 ± 6.3	172.9 ± 5.5	172.7 ± 8.3	173.8 ± 8.3
BMI	22.7 ± 3.1	22.5 ± 2.8	24.4 ± 2.8	24.1 ± 2.7
Leg Length (mm)	912 ± 41	906 ± 34	904 ± 48	900 ± 53
Foot Length (mm)	252 ± 13	251 ± 17	252 ± 17	251 ± 17
Foot Width (mm)	95.6 ± 5.3	94.8 ± 4.8	99.6 ± 8	99.3 ± 8
Toe Length (mm)	68 ± 5.6	68 ± 3.9	69 ± 9.7	68 ± 5.2
Nav. Height (mm)	48 ± 7.4	48 ± 6.7	49 ± 7.3	46 ± 5.1
Reported weekly activity (Hrs)	31.3 ± 20.8		25 ± 25.1	
Weekly reported Footwear Use (Hrs)	49.2 ± 17.3		52.7 ± 17.3	

All MFA participants pre-intervention period, EMS, and HBM biometric data is shown in Table 3.2. Table 3.3 shows the biometric comparisons between the three groups. The biometrics from the MFA and EMS groups were very similar, with only navicular height being statistically significantly greater in the EMS group. The biometrics of the HBM group proved to be highly different from the MFA and EMS groups' biometrics. Only age and Toe length were not statistically different.

*Table 3.2: Biometric comparisons between the three groups. * The HBM group has some missing biometric data, of the 15 HBM participants tested; age was reported for 12, leg length was reported for 8, and navicular hieght reported for 13. Foot length and width was not measured.*

Biometrics	MFA (n = 46)	EMS (n = 20)	HBM (n = *15)**
Age (yrs)	27.6 ± 6.9	31.05 ± 7.1	32.2 ± 9.7*
Mass (kg)	70.3 ± 12.5	68.6 ± 9.4	49.4 ± 9.2
Height (cm)	172.4 ± 7.3	173.5 ± 9.8	157.7 ± 7.9
BMI	23.5 ± 3	22.8 ± 2.9	20 ± 4.1
Leg Length (mm)	908 ± 44	933 ± 52	797 ± 47*
Foot Length (mm)	252 ± 15	255 ± 16	-
Foot Width (mm)	97 ± 6.9	98 ± 7.8	-
Toe Length (mm)	69 ± 8	70 ± 7	64 ± 5
Navicular Height (mm)	48 ± 7	53 ± 7	40 ± 5*

Table 3.3: Biometric comparisons between total MFA group, pre-intervention period, EMS group and HBM group. Statistical differences were detected via one way ANOVA comparisons followed by a post-hoc test for most of the biometrics. p-values for both foot length and width comparisons between the MFA and EMS group was calculated with unpaired t-tests.

p-values for Biometric Comparisons between the three Groups

Biometrics	MFA vs EMS	MFA vs HBM	EMS vs HBM
Age	0.2	0.14	0.91
Mass	0.83	**<0.001**	**<0.001**
Height	0.87	**<0.001**	**<0.001**
BMI	0.69	**0.0013**	**0.034**
Leg Length	0.12	**<0.001**	**<0.001**
Foot Length	0.42	-	-
Foot Width	0.76	-	-
Toe Length	0.71	0.15	0.07
Nav. Height	0.03	**<0.001**	**<0.001**

3.5.2. Footwear Properties

Table 3.4 shows footwear spatial and material properties of the Vivobarefoot Stealth II trainers given to the MFA intervention participants (Min), the 'conventional' footwear worn by all MFA participants, pre-intervention period (MFA), and the footwear worn by the EMS participants on the day of testing (EMS). Table 3.5 shows the comparisons between these footwears. Both the intervention footwear and the EMS footwear proved to be very similar with upper thickness being only statistically significant difference between the two groups. The conventional western footwear brought in by the MFA participants proved to be highly variable and definitely more so than the minimal footwear worn by the EMS participants. The MFA shoes proved to be statistically significantly different when compared to the invention footwear in all attributes tested with the exception of shoe length, and given that the intervention footwear tested was selected based on average MFA foot length, this is not surprising.

Table 3.4: Footwear spatial and material properties of the Vivobarefoot Stealth II trainers given to the MFA intervention participants (Min), the 'conventional' footwear worn by all MFA participants, pre-intervention period (MFA), and the minimal footwear worn by the EMS participants on the day of testing (EMS).

Footwear Properties	Min (n = 5)	MFA (n = 46)	EMS (n = 20)
Sole Thickness (mm)	5	32.6 ± 44.7	7.9 ± 4.4
Upper Thickness (mm)	0.5	3 ± 1.6	1.5 ± 1.2
Sole Offset (mm)	0	12.2 ± 8.5	0.2 ± 4.6
Shoe Length (mm)	284	285 ± 20	275 ± 24
Shoe Width (mm)	106.7	101.5 ± 6.7	104.4 ± 9.4
Shoe Weight (g)	202	350 ± 105	199 ± 38
Bending Stiffness (N)	5.48 ± 0.16	13.25 ± 6.17	-
Sole Softness (mm/N)	0.022 ± 0.003	0.079 ± 0.031	-

Table 3.5: Footwear spatial and material properties comparison between the Vivobarefoot Stealth II trainers given to the MFA intervention participants (Min), the "conventional" footwear worn by all MFA participants, pre-intervention period(MFA) and the footwear worn by the EMS participants on the day of testing (EMS). Statistical differences were detected via one way ANOVA comparisons followed by a post-hoc test.

p-values for Footwear Properties Comparisons between the three Groups			
Biometrics	Min vs MFA	Min vs EMS	MFA vs EMS

p-values for Footwear Properties Comparisons between the three Groups			
Sole Thickness	**<0.001**	0.48	**<0.001**
Upper Thickness	**<0.001**	0.03	**<0.001**
Sole Offset	**<0.001**	0.1	**<0.001**
Shoe Length	0.97	0.27	0.11
Shoe Width	**0.013**	0.51	0.25
Shoe Weight	**<0.001**	0.99	**<0.001**
Bending Stiffness	**<0.001**	-	-
Sole Softness	**<0.001**	-	-

3.5.3. Participant History

Information gathered from the future footwear questionnaire was collated in Table 3.6. Un-paired t-tests were used to discover any statistically significant differences between the two groups. It can be seen in Table 3.6 that both MFA and EMS participants' general weekly activity and age of their current most frequently worn types of footwear were not significantly different from one another before the start of the study. Whereas the time spent in their respective footwear types was statistically significantly different before the start of the study, with the MFA group being conventionally western shod for a greater time the EMS group had been minimally shod for. Furthermore, weekly use of the group's respective regular footwear was statistically significantly higher in the EMS group than the MFA group, before the start of the study.

Table 3.6: Participant and footwear history comparisons between the total MFA group, pre intervention period and EMS group. p-values were calculated via unpaired t-tests. p-values of <0.05, <0.01 or <0.001 were represented by '','**', and '***' respectively.*

Footwear Use and Activity	MFA (n = 46)	EMS (n = 20)
General Activity per week (Hrs)	28.3 ± 22.9	38.7 ± 33.1
Regular footwear age (yrs)	1.1 ± 0.8	1.5 ± 1.3
Time spent in Regular Footwear type (yrs)	8.8 ± 6.3***	2.5 ± 2.4***
Weekly use of Regular Footwear (hrs)	50 ± 16.8**	70.2 ± 25.2**

3.5.4. Toe Flexion Strength

MFA control and intervention group change in TFS is shown in Figure 3.5. It can be seen in Figure 3.5 that there is no significant change in TFS for the control group (4.4 ± 33.7%, p = 0.98) and significant change in TFS for the intervention group (57.4 ± 68.4%, p<0.001). The effect size of the change in TFS of the intervention group was calculated and gave a Cohen's "d" value of 0.84, representing a large effect.

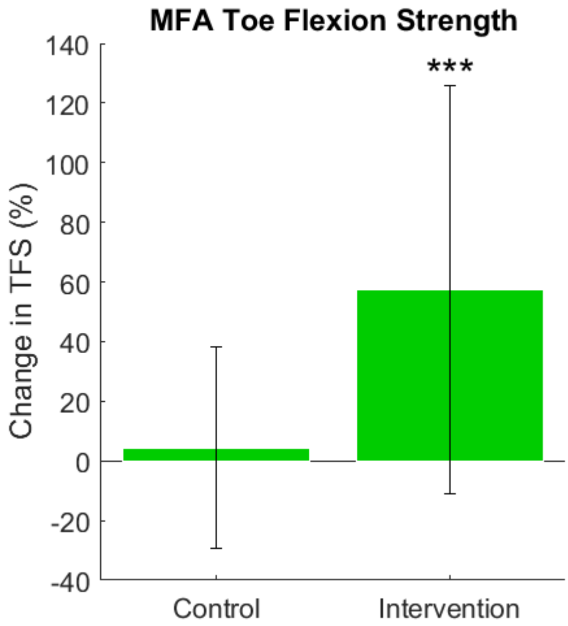

*Figure 3.5: Change in TFS at the end of the longitudinal study compared to the start. Where p-value <0.001 is represented by "***".*

For the cross-population comparison, TFS was normalised to body mass. TFS per unit mass for MFA intervention sub-group, pre and post intervention period, EMS group, and HBM group is shown in Figure 3.6. It can be seen in Figure 3.6 that the MFA intervention sub-group, post-intervention period has TFS per unit mass that is statistically significantly greater ($p = 0.017$) than the MFA sub-intervention group, pre-intervention period. EMS group TFS per unit mass was also statistically significantly ($p = 0.048$) greater than the MFA sub-intervention group, pre-intervention period. The HBM group had the greatest relative variation of results and proved to be not statistically significant between any of the other groups.

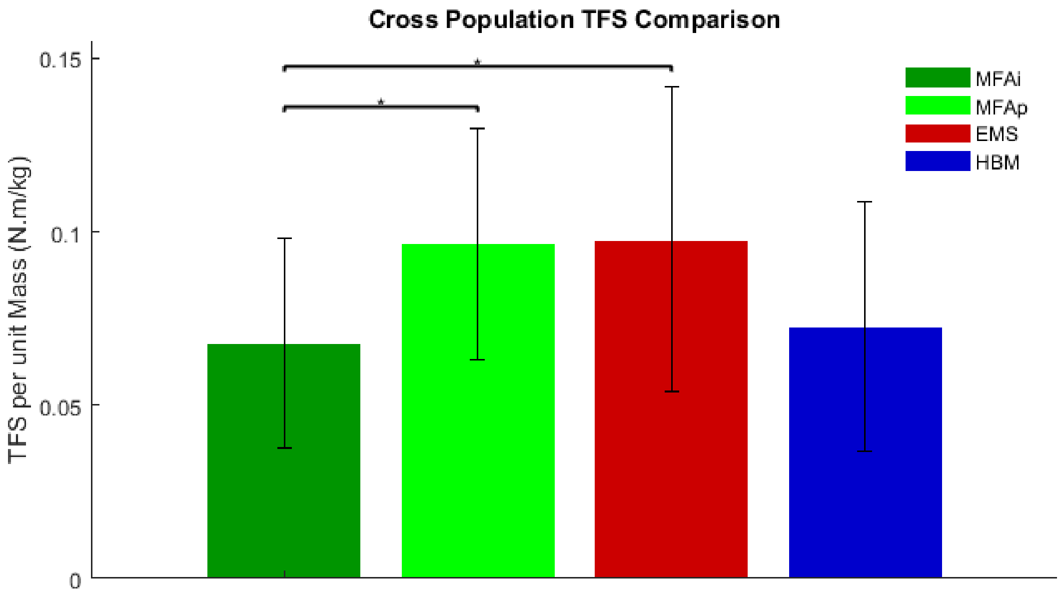

Figure 3.6: Toe flexion strength per unit mass of the three different groups. Left to right: (MFAi) Minimal footwear adaption study – intervention group at the start of the study. (MFAp) Minimal footwear adaption study – intervention group at the end of the study. (EMS) Experienced minimally shod. (HBM) Habitually minimally shod. MFAi vs. MFAp, p = 0.017. MFAi vs. EMS, p = 0.048. P-Values <0.05 were represented by "".*

3.6. Discussion

It can be seen from Table 3.1 that there was no increase in foot width after conventionally western shod regularly used minimal footwear for a six-month period, thereby rejecting the first hypothesis of this study. Interestingly, even the foot width of experienced minimally shod walkers was not statistically significantly wider than foot widths of conventional western shod participants that have never worn minimal footwear before. The lack of change of foot width may be due to foot placidity of adults being much lower than that of children (Hollander et al., 2017a). This could explain why habitually barefoot and or minimally shod populations have wider feet than habitually conventionally western shod populations (Ashizawa et al., 1997, Hollander et al., 2017b, D'Août et al., 2009) but we observed no increase in foot width for all habitually conventionally western shod adults that transitioned to minimal footwear in adulthood. Even though no changes in foot width at the level of the ball of the foot were detected in this study because of six months (or more than six months) of regular minimal footwear use, we expect foot width measured as the distance between the tip of the hallux and little toe would have increased.

This is because many MFA intervention participants reported that their toes appeared more spread out by the end of the study. There is currently no literature on the long-term influence of minimal footwear use on this type of measure for foot width and nor did we record this metric. Future studies should investigate the influence of long-term minimal footwear use on this measurement of foot width.

MFA intervention group navicular height was similar pre and post intervention period, however EMS group navicular height was significantly higher than MFA group navicular height, pre intervention period. This suggests that regular minimal footwear use for periods of time greater than six months will increase static longitudinal arch height. The current literature on longitudinal arch height is conflicting. Some studies found habitually barefoot and/or indigenously minimally shod participants had greater static longitudinal arch height than habitually conventionally western shod (Lieberman, 2014, Hollander et al., 2017a), whereas D'Août et al. (2009) found no differences in longitudinal arch height. However, D'Août et al. (2009) noted that the variation in longitudinal arch heights were much less varied in the habitually barefoot group and much more varied in the habitually conventionally western shod group. This suggests the habitually conventionally western shod communities are prone to extreme foot morphologies that can result in foot pathologies than habitually barefoot communities. This could also explain why EMS group navicular height is greater than the MFA group; the long-term use of minimal footwear by the EMS group increased longitudinal arch height in just the participants that had very low arches thereby increasing the average navicular height. The HBM group were found to have significantly lower navicular heights however we believed this to be caused by population differences as opposed to footwear wearing habits, as African populations have been shown to have lower medial-longitudinal arch heights than European populations (Stolwijk et al., 2013). This may also explain the contradictions in literature on longitudinal arch height as all the studies used different populations from around the world.

Figure 3.5 shows MFA participants who regularly wore minimal footwear for the six-month intervention period increased toe flexion strength by 57.4% ($p<0.001$, d =

0.84). This agrees with the research by Ridge et al. (2019), where after 8 weeks of walking in minimal footwear, foot strength increased by 41.11%. As regular use of minimal footwear was the only intervention introduced for the intervention period and as the control group showed no changes it must be concluded that daily activity in minimal footwear increases foot strength for healthy adults. A finding in line with our second hypothesis. Foot strength most likely increased from daily activity in minimal footwear, due to its significantly lower bending stiffness. The soles of conventional footwear are typically harder to dorsiflex about the MPJ. This stiffness contributes to the resistive force required for the foot to be a stiff lever upon push-off, thereby reducing the role of the intrinsic foot muscles during gait. Overtime this will prevent intrinsic foot muscle growth. On the other hand, a more flexible sole has been associated with second metatarsal stress injury during relatively high-intensity walking (Arndt et al., 2003). It is therefore important to transition to minimal footwear use slowly and with caution, to promote foot muscle growth, while not overloading the foot and increasing injury risk.

Figure 3.6 shows that previously habitually conventionally western shod adults with at least six months experience in minimal footwear have greater TFS per unit mass than the conventionally western shod with no minimal footwear experience. In addition to this, TFS per unit mass of previously habitually conventionally western shod individuals with just six months experience of regular minimally shod walking is very similar to previously habitually conventionally western shod adults with 2.5 ± 2.4 years minimally shod walking experience. A finding that rejects the third hypothesis. This strongly suggests that six months of using minimal footwear on a regular basis is a sufficient time period to increase intrinsic foot muscle strength to their natural intended strength. In fact, the intrinsic foot muscle strength could be optimised in less time. A time period between 8 weeks and six months of regular minimal footwear use is highly likely to optimise foot strength, given that Ridge et al. (2019) found foot strength of habitually conventionally western shod adults increase by ~40% after 8 weeks of regular use of minimal footwear, and the present study found an increase of ~60% for six months.

Obtaining a naturally strong foot could be important to conventionally western shod individuals wishing to run in minimal footwear. Many previous studies have shown that minimally shod running can be detrimental to musculoskeletal health (Ridge et al., 2013, Davis, 2014). All these studies started with participants with none or very little experience with minimal footwear. Injury free minimally shod running may be possible once sufficient foot strength is reached (whether it be through foot strengthening exercises or gentle walking in minimal footwear over a sufficiently long time period). However, it is likely that foot strength in only one piece of the puzzle. We hypothesis that the bones of the foot require sufficient time to strengthen as well as time spent learning correct minimally shod running technique for minimally shod running to be a safe and healthy activity for a conventionally western shod population. Increased mechanical loading on the bone promotes bone growth (Frost, 1994). Therefore, regular walking in minimal footwear may be more beneficial than just foot strengthening exercises on its own as minimally shod walking will both strengthen the foot muscles and bones. We therefore conclude, one must walk before they can run when it comes to minimally shod locomotion.

Finally, the fourth hypothesis, conventionally western shod adults will have comparable foot strengths to habitually barefoot and/or minimally shod adults given sufficient minimally shod walking experience, was found to be inconclusive. This is because of limitations associated with the HBM study. The group was too small and not enough biometrics or participant footwear habit history had been collected. The footwear wearing habits of HBM group investigated were not as clear as originally assumed. The Ju|'hoan San from the Nyae-Nyae Concession Area, Otjizondjupa region are traditionally habitually minimally shod however in recent years some conventional western footwear use has been adopted. Therefore, it is possible that some of the HBM participants' foot strength was reduced by conventional footwear use. This could also explain why HMB group TFS standard deviation was so high. As a result, we believed that the results did not hold enough validity to accept or reject this hypothesis. More in-depth research is required to determine if habitually barefoot and/or minimally shod populations have the greater relative foot strength than conventionally western shod populations.

Overall, this study has shown that regular use of minimal footwear increases foot strength, in a conventionally western shod population. Increasing foot strength is likely to reduce the chance of developing foot deformities associated with weak intrinsic foot muscles such as Hallux Valgus (Soysa et al., 2012), claw toe and hammer toe (Myerson and Shereff, 1989). Additionally, Mickle et al. (2009) discovered that intrinsic foot muscle strength directly links to stability. It has also been shown that increasing intrinsic foot muscle strength has been shown to positively influence balance and stability and reduces fall risk in older people (Spink et al., 2011). This is of particular importance as nearly one third of older people experience at least one fall a year (Todd and Skelton, 2004) impacting on their quality of life. This suggests that regular and gentle use of minimal footwear has the potential to be beneficial to long term musculoskeletal health.

3.6.1. Limitations

It should be noted that TFS is most likely a combination of both intrinsic and extrinsic foot muscles. Extrinsic foot muscles cover many of the same functions as intrinsic foot muscles (Ridge et al., 2017) therefore it is unlikely that the increase in TFS is completely caused by an increase in intrinsic foot muscle strength. However, intrinsic foot muscle strength will have increased, it is just not possible to directly quantify in the present study.

Another limitation in the study was that competition is not a familiar concept in San culture and that combined with the language barrier made it difficult to convey the MVIC motion required to measure TFS. This may have contributed to TFS being lower than expected.

3.7. Conclusion

Daily activity in minimal footwear increases foot strength for healthy adults that were previously conventionally western shod. Regular use of minimal footwear also had limited influence on arch height but no influence on foot width.

3.8. Acknowledgments

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4. Chapter 4: A prospective study on transitioning to regular minimal footwear use and its influence on plantar pressures in barefoot, minimally shod and conventionally shod walking

4.1. Chapter 4 Covering page

4.1.1. List of Authors

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4.1.2. Author Contributions

Rory Curtis: Conceived, designed, and carried out the study, wrote the chapter, and edited the chapter.

Catherine Willems: Supervised and guided chapter write up.

Kristiaan D'Août: Provided supervision and guidance for all aspects of the project and chapter.

4.1.3. Chapter 4 Foreword

The differences in toe flexor strength observed in chapter three are likely to be caused by differences in plantar pressure characteristics as a result of minimally shod walking. Therefore, this chapter evaluates barefoot, minimally shod and conventionally shod walking spatial and temporal plantar pressure characteristics. This will also answer an aspect the first central research question: What differences exist between barefoot, minimally shod and conventionally shod walking in healthy adults? It also evaluates the influence of regularly walking in minimal footwear on spatial and temporal plantar pressure characteristics while walking barefoot, minimally shod and conventionally shod, in order to answer an aspect of the second central research question: Can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function? To answer both questions, the MFA group was utilised in this chapter as well as in chapter three. The MFA group had their planter pressures measured while walking barefoot, minimally shod, and conventionally shod, pre and post the six-month intervention period. In addition to this the EMS group (that had their foot strength tested within chapter 3) also had their plantar pressures measured while walking barefoot and minimally shod to answer an aspect of the third central research question: What are the long-term effects of walking in minimal footwear? Given that both this chapter and chapter 3 use the EMS and MFA group, there is potential for a connection to be made between foot strength and plantar pressure characteristics. Overall, this chapter evaluated the following hypotheses:

- Minimally shod walking peak plantar pressure will be less than barefoot walking and greater than conventionally shod walking for habitually conventionally western shod adults.
- Inexperienced minimally shod walkers will heel strike most distally when walking barefoot and least while walking conventionally shod, with minimally shod walking as an intermediate for habitually conventionally western shod adults.
- Six months of regular minimal footwear use will produce minimally shod walking peak plantar pressure distributions statistically indistinguishable from their barefoot plantar pressure distributions.
- Six months of regular minimal footwear use will lead to minimally shod walking heel-to-toe plantar pressure progression throughout stance phase being closer to that of barefoot walking.

4.2. Abstract

Walking in minimal footwear has been described to exhibit gait characteristics closer to barefoot walking than walking in conventional modern-day footwear, while still offering protection for the feet from the environment. However, this

conclusion is based on limited research. In addition to this, no research has questioned if a familiarisation period is required for effective minimally shod walking, like it is for minimally shod running. As a result, this study aims to:

1. Define the differences between barefoot, minimally shod, and conventionally shod walking via their plantar pressure characteristics for healthy conventionally western shod adults.
2. Define how experience of regularly walking in minimal footwear during a familiarization period influences all three walking conditions.

To investigate these aims, peak plantar pressure distributions and Centre of Pressure (CoP) trajectories were derived from participants walking barefoot, minimally shod and in their conventional footwear. Participants were then allocated minimal footwear to wear for six months. At the end of the six-month period, the same plantar pressure characteristics were derived again. For the purposes of reference this study is referred to as the minimal footwear adaption (MFA) study. This research goes on to compare the findings from the MFA study to an additional group to add further insight on the influence of long-term minimal footwear use. This was a group of previously habitually conventionally western shod adults with 2.5 ± 2.4yrs experience in minimal footwear (EMS). The EMS group also had their peak plantar pressure distributions and Centre of Pressure (CoP) trajectories evaluated during walking.

CoP results showed minimally shod walking to be intermediate between barefoot and conventionally shod walking, whereas peak plantar pressure distributions showed no statistically significant differences between any of the walking conditions. Both CoP and peak plantar pressure distributions showed that six months of regular minimal footwear use has no impact on stance phase for healthy conventional western shod adults, based on both plantar pressure characteristics reported in this study. Furthermore, EMS group plantar pressure distributions and CoP trajectories were comparable to those of the MFA group, suggesting that long-term minimal footwear use has no influence on plantar pressure characteristics during walking.

4.3. Introduction

There exists a plethora of footwear options. From high heels to trainers, and flip flops to boots, the types of footwear options available in modern western communities are highly variable and difficult to define. For the purposes of this study these types of footwear were grouped as conventional footwear due to how commonly they are worn throughout our daily lives. Another type of footwear that has increased in popularity, in western communities, over recent years is minimal footwear (Davis, 2014, Hryvniak et al., 2014). Minimal footwear is defined as "Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices" (Sinclair et al., 2013). In short, it is footwear that is meant to simulate being barefoot. Although minimal footwear has recently gained popularity in western communities, there is nothing new about either minimal footwear or walking barefoot.

We have walked barefoot for much of our evolutionary history. Modern Homo *sapiens* are estimated to be almost 200,000yrs old (McDougall et al., 2005), whereas footwear is believed to have only existed from around 40,000 years ago, based on fossil records revealing changes in the lessor toes (Trinkaus, 2005). The oldest archeological evidence for footwear has been carbon dated at around 8300 years old (Kuttruff et al., 1998). The footwear discovered by Kuttruff and colleagues was made from a very modest construction of fibrous plant material and offered very little in terms of support (Kuttruff et al., 1998). These shoes can be classified as minimal footwear and are comparable to modern day moccasins. Footwear continued to be minimal in construction for thousands of years. It has only been post-industrial revolution (the last 200 years) that footwear with a heeled support has become accessible and popular to the majority of the population (Shawcross, 2014). In fact, it has only been in the last 50 years that complex support mechanisms have been incorporated into footwear design (Shawcross, 2014, Lieberman et al., 2010, Shorten, 2000), with the invention of the cushioned running shoes in the 1970s (Cavanagh, 1980). Given that our ancestors not only survived but thrived during times they were barefoot or even minimally shod, it must be questioned how necessary conventional footwear is. Some studies have gone as far to say conventional footwear could be a possible factor to running injuries (Lieberman et al., 2010, Robbins and GOUW, 1989, Robbins et al., 1993, Divert et al., 2005).

Despite how commonly conventional footwear is used in the modern western world, little thought is given to their influence on our musculoskeletal health. A multitude of studies have shown high heels to be detrimental to our musculoskeletal health (Lee et al., 2001, Kerrigan et al., 1998, Csapo et al., 2010, Cronin et al., 2012, Barnish and Barnish, 2016). Early researchers comparing habitually barefoot and/or minimally shod communities to conventionally shod ones, found foot deformities and pathologies to be much greater in conventionally shod communities (Hoffmann, 1905, Sim-Fook and Hodgson, 1958, Shulman, 1949). Findings further supported by recent research comparing skeletal foot pathologies post to pre-industrial revolution skeletons (Zipfel and Berger, 2007, Mafart, 2007). This suggests that conventional footwear could be detrimental to our long term musculoskeletal health.

Studies have argued that running in minimal footwear reduces injury risk (Lohman et al., 2011, Lieberman et al., 2010, Divert et al., 2005, Jenkins and Cauthon, 2011). However, studies have also found transitioning to minimally shod running could cause metatarsal stress injuries (Giuliani et al., 2011), as well as bone marrow edema (Ridge et al., 2013). As popularity in minimally shod running increased so did the injury rate (Davis, 2014). This led to a reduction in enthusiasm for both minimally shod running as well the research around it. However, in recent years minimally shod walking has started to be investigated again. A recent systematic review found minimal footwear elicits walking kinematics closer to barefoot walking than conventionally shod walking, but significant differences still exist between minimally shod walking and barefoot walking (Franklin et al., 2015). Franklin et al. (2015) also found the level of footwear familiarity to influence gait velocity. This could cause issues with cross-sectional study designs that investigate the differences between footwear conditions as participant familiarity with one type of footwear and unfamiliarity with another add a potentially unintended co-variant to a study.

Therefore, care is taken within the present chapter when making comparisons between different groups.

Plantar pressure measurements offer an additional perspective on how the plantar surface of the foot is loaded with respect to the supporting surface, making it useful for musculoskeletal biomechanical analysis (Orlin and McPoil, 2000). Plantar pressure measurements are often used for clinical applications focusing on obesity (Hills et al., 2001, Rosenbaum et al., 1994, Dowling et al., 2001, Birtane and Tuna, 2004) and diabetes (Cavanagh and Ulbrecht, 1994, Abouaesha et al., 2001). However, plantar pressure measurement's ability to easily capture great foot loading detail, makes it an ideal analysis method to analyse the influence of footwear.

Plantar pressure measurements can be used to characterise total force distribution under the sole of the foot throughout stance phase, which typically are represented as peak plantar pressure distributions. It can also characterise foot roll-off qualities. Which typically are represented as centre of Pressure (CoP) trajectories. Plantar pressure measurements have been used to characterise healthy barefoot running in conventionally western shod communities (De Cock et al., 2008). Analysis of plantar pressure has also revealed more anterior foot strikes for conventionally western shod communities when minimally shod running once experience in minimal footwear had been gained (Warne et al., 2014, Moore et al., 2015). Moore et al. (2015) also found peak plantar pressures were reduced while running in all the conditions tested (barefoot, minimally shod, or conventionally shod) after experience had been gained in minimally shod running. Conventionally western shod communities have been shown to have relatively greater stress concentrations within some regions of the foot in relation to the rest of the foot, when compared to habitually barefoot and minimally shod communities, while walking barefoot (D'Août et al., 2009). Yet, to the best of our knowledge, no research has been conducted using plantar pressure analysis to investigate stance phase changes due to familiarisation to walking in minimal footwear, for conventionally western shod communities. Therefore, the present study will investigate two groups with varying experience in minimal footwear use, including one prospective group to gain as much insight into the timescale the influence of regular minimal footwear use has on plantar pressure. The present study characterises minimally shod walking in comparison to barefoot and conventionally shod walking and investigates the influence familiarisation to minimally shod walking has on all three walking conditions. The aims of the present study are as follows:

1. Define the differences between barefoot, minimally shod and conventionally shod walking via their plantar pressure characteristics for healthy conventionally western shod adults.
2. Define how experience of regularly walking in minimal footwear during a familiarisation period influences all three walking conditions.

Given the aims of the present study, we hypothesised the following:

1. Minimally shod walking peak plantar pressure will be less than barefoot walking and greater than conventionally shod walking.
2. Six months of regular minimal footwear use will produce minimally shod walking peak plantar pressure distributions statistically indistinguishable from their barefoot plantar pressure distributions.
3. Inexperienced minimally shod walkers will heel strike most distally when walking barefoot and least while walking conventionally shod, with minimally shod walking as an intermediate.
4. Six months of regular minimal footwear use will lead to minimally shod walking heel-to-toe plantar pressure progression throughout stance phase being closer to that of barefoot walking.

4.4. Methods

The present study combines both prospective study design and cross-population study design to gain greater insight into the influence regular minimally shod walking has on habitually conventionally western shod adults. The study investigates the influence six months of daily activity in minimal footwear has on peak plantar pressure distributions and Centre of Pressure (CoP) trajectories during walking, for adults that were previously habitually conventionally western shod.

For the purposes of reference this study is referred to as the minimal footwear adaption (MFA) study. This research goes on to compare the findings from the MFA study to an additional group to add further insight onto the influence of long-term minimal footwear use. This was a group of previously habitually conventionally western shod adults with 2.5 ± 2.4yrs experience in minimal footwear (EMS). The EMS group also had their peak plantar pressure distributions and Centre of Pressure (CoP) trajectories during walking evaluated.

4.4.1. Minimal Footwear Adaption (MFA) Study Experimental Procedure

51 healthy participants (30 male, 21 female; 27.6 ± 6.9yrs, 23.6 ±3.1 BMI) with no previous experience of wearing minimal footwear were recruited to take part in a six-month longitudinal study, where dynamic plantar pressure measurements were taken before and after the six month period. 22 of these participants (13 male, 9 female, 26.7 ± 6yrs, 24.4 ± 2.7 BMI) wore minimal footwear allocated to them (Vivobarefoot Stealth II shoes) for the six-month intervention period. These participants are referred to as the MFA – intervention sub-group. The MFA – intervention participants were required to wear the minimal footwear for a minimum of 70% of their time shod, as well as at least six days a week. 24 of the participants (14 male, 10 female, 28.4 ± 7.4yrs, 22.8 ± 3.1 BMI) continued to wear the footwear they most regularly wore for the intervention period. These participants were referred to as the MFA – control sub-group. The MFA – control sub-group were required to wear their regular footwear to the same constraints as the MFA – intervention sub-group. All MFA participants filled out a participant activity logs on a weekly basis to monitor their footwear wearing habits. The five remaining participants dropped out due to injury (unrelated to the study) or failure to meet the study requirements.

At the start of the study all MFA participants came to the University of Liverpool Gait Lab to have key biometrics and plantar pressure measurements recorded. The plantar pressure measurements were taken using the following methodology. The participants were instructed to walk (at a self-selected speed) down a 12m walkway over a plantar pressure plate (FootWork® Pro, AMCube IST, France), for three different walking conditions: barefoot, conventionally shod, and minimally shod. The plantar pressure plate has 4,096 7.6mm squared capacitor type sensors that yields one pressure sensor per 5mm squared, and a sample frequency of 200Hz. Participants continued to walk down the walkway until three left and three right trials were recorded by the pressure plate for each condition. At the end of the six-month intervention period, the plantar pressure measurements were recorded again following the same methodology.

4.4.2. Experienced Minimally Shod (EMS) Study Experimental Procedure

20 healthy experienced minimally shod walkers from a habitually conventionally western shod background (EMS group; 2.5 ± 2.4yrs minimal shod walking experience, 10 female, 10 male, 31.1 ± 6.7 yrs, 22.8 ± 2.7BMI) had plantar pressure measurements recorded following the same methodology as the MFA group. EMS participants only walked over the plantar pressure mat while barefoot and minimally shod, no conventionally shod walking plantar pressure measurements were recorded. In addition to this, plantar pressure readings for the EMS participants were only collected once. EMS participants were recruited if they had at least six months experience of regularly walking in minimal footwear.

4.4.3. Analysis

The same analysis procedure was applied to both MFA and EMS group plantar pressure prints. Peak plantar pressure distributions and Centre of Pressures (CoP) were calculated for both groups. Peak plantar pressure distributions were analysed via Pedobarographic Statistical Parametric Mapping (pSPM). pSPM registers prints so that they optimally overlap with one another, and then statistically compares the optimally overlapped prints at the pixel level (Pataky and Goulermas, 2008).

In addition to the pSPM analysis, centre of pressure (CoP) trajectories were calculated. In order to understand CoP trajectories, we must first understand CoP. CoP is the centroid of vertical ground reaction force distribution (Benda et al., 1994), which can be derived from any given time frame of a plantar pressure print. CoP trajectories are the displacement of this centre of pressures from all plantar pressure print time frames throughout stance phase, for any given print. The CoP trajectories in this paper used the optimal scaling transformations from pSPM (Pataky et al., 2014) to create 2D – CoP trajectories that represent both proximal-distal and medial-lateral dimensions.

4.4.3.1. Print Pre-processing

Pre-processing of the prints was required to get the prints ready for both pSPM and 2D-CoP analysis. The following pre-processing steps were followed:

1. All plantar pressure prints were extracted from the AMCube software and saved into a csv. file.
2. Prints were then uploaded into Matlab2017a were each print was represented as a 3D matrix (width X length X time).
3. The data resolution was up-sampled so that each cell size in was 5mm^2 (width X height, through time).
4. All the left prints were flipped making them equivalent to right prints. Any prints that were upside down were rotated 180° so that they were facing the same direction.
5. The 3D matrices of each print were converted into 2D matrices by calculating the maximum pressure during each time frame. These 2D matrices were then saved. The same can be done by taking the impulse of each 3D matrix and will ultimately produce similar results. Max pressure was taken as it proved to be easier to register for the processing required for pSPM.
6. The saved 2D matrices from before were printed and examined in order to ensure that all prints were free from defects (e.g., make sure that no prints were cut off or more than one print was in in the image), correctly oriented (e.g., all prints were right and facing upwards) and that there were no duplicates. Any prints that needed correcting were dealt with manually at step four and were saved with the rest of the already suitable prints.
7. Maximum pressure was then taken from the 3D matrix analysis ready prints in order to produce 2D matrix analysis ready prints.

Once the pre-processing was completed, the 2D matrix analysis ready prints were ready for registration leading to pSPM analysis, and the 3D matrix analysis ready prints were then ready to begin the 2D CoP analysis.

4.4.3.2. Pedobarographic Statistical Parametric Mapping (pSPM)

The 2D analysis ready prints were processed using the following pedobarographic statistical parametric mapping (pSPM). The processes involved with pSPM are detailed below:

1. All prints were spatially smoothed and saved as sparse matrices.
2. Prints within-subjects for a given condition, were registered using an optimal rigid body transformation. Transforming the prints proceeding the first print within a participant to the first print, so that all prints within-subjects were aligned to the first.
3. Average prints were calculated from the aligned within-subject prints.
4. Step two was performed again, this time with all within-subject prints being registered to their respective average prints, in order to remove any bias from registering to the first print in the within-subject array, at the first stage of registration – creating a second wave of aligned within-subject prints.
5. New average within-subject prints were calculated from second wave of aligned within-subject prints.
6. The new average within-subject prints were registered between themselves using optimum affine transformations. Transforming all the averaged within-subject prints to the first one, so that the averaged within-subject prints were all aligned to the first one.
7. All the registered between-subject prints were visually inspected, and manual registration was performed on incorrectly-registered prints when required.
8. An average print was calculated from all of the aligned averaged within-subject prints.
9. Step six was then performed again, this time with all the averaged within-subject prints being registered to the average of all of the averaged within-

subject prints in step seven (this was done in order to remove any bias from registering to the first within-subject prints). This generated an array of between-subject registered prints.

10. All the registered between-subject prints were visually inspected, and manual registration was performed on incorrectly-registered prints when required.
11. A final average print was then calculated from the between-subject registered prints. In the present study, this final average print is referred to as the condition average print.
12. Steps 1 – 11 were then repeated for the remaining conditions.
13. Once the prints for all three conditions (barefoot, minimally shod, and conventionally shod walking) had been processed to the point that their respective condition average print had been generated, processing between the conditions could begin.
14. Both the minimally shod and conventionally shod average print were registered to the barefoot average print to generate transformation parameters to be used on the minimally and conventionally shod between subject prints, respectively. The newly registered minimally and conventionally shod average prints were discarded, and the original minimally shod and conventionally shod average prints were kept (these prints will be used for the 2D – CoP methods).
15. The minimally and conventionally shod transformation parameters generated in step 14 were applied to the minimally shod and conventionally shod between-subject registered print arrays, respectively. This was done so that the prints in the between-subjects arrays were all aligned and scaled between walking conditions.
16. The prints were then ready for pSPM analysis. pSPM comparisons were made between the registered walking conditions. Raw t-values of the statistical inference where cooler colours (blue) correspond to pixels where the primary walking condition pressure is higher and warmer colours (red-yellow) correspond to pixels where the secondary walking condition is

higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05).

When using pSPM analysis, comparisons can only be made in pairs. As a result, a barefoot vs. minimally shod and a barefoot vs. conventionally shod comparisons were done separately.

4.4.3.3. 2-Dimensional Centre of Pressure (CoP) using Optimal Scaling Transformations

To generate 2D CoP using optimal scaling transformations, further processing of the pre-processed data was required. The 3D matrix analysis ready prints were taken as the starting point. The prints were linearly interpolated about the temporal axis in order to normalise the stance time for each print, thereby making time-based comparisons between steps possible. The 3D matrices were linearly interpolated from 1 – 101 frames, so that each frame would represent 1% of the stance phase. The data was then spatially normalised using a modified methodology for optimal scaling transformations developed by Pataky et al. (2014). In the present study the methodology was as follows:

1. The linearly interpolated 3D matrices were converted into 2D matrices by taking the maximum pressure from each temporal frame to generate reference prints for every print in this study.
2. The barefoot average print from the pSPM analysis was taken and rotated such that the prints calculated least squares regression line was vertical, as can be seen in Figure 4.1.

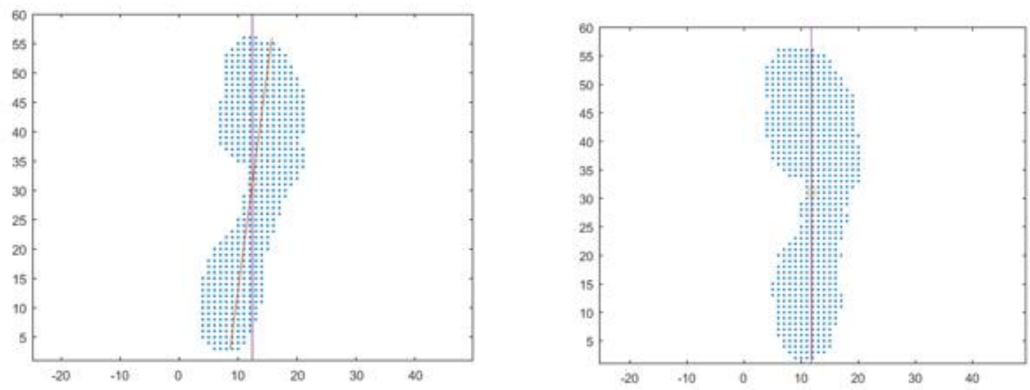

Figure 4.1: Image illustrating the rotation method applied to the barefoot average print.

3. The minimally and conventionally shod average prints were then aligned to the barefoot average prints by using just the rotational and translational aspects of the optimum affine transformations. This was done so that all average condition prints were aligned and vertical but not scaled to be the same size as one another.
4. These reference prints were then registered to their respective condition average print. The registration used in this case was optimum affine transformations. The registered reference prints were visually inspected to ensure that all the reference prints were correctly registered. All incorrectly registered prints were manually registered. The transformation parameters were then saved for each registration.
5. The transformation parameters were then applied to their respective corresponding 3D matrix print, where the respective transformation parameter was applied to each temporal frame (from 1 – 101) of a given 3D matrix print. This was done so that every frame within all 3D matrices were aligned to their respective condition print. Ultimately this meant that all 3D matrix prints were aligned between conditions as the condition prints are all aligned to one another.
6. Average subject 3D matrix prints were then calculated.
7. CoPs were calculated as the position of average pressure for each frame of all the average subject 3D matrix prints.

8. These CoPs were linked together through the temporal axis of the 3D prints to generate CoP trajectories.

4.5. Results

4.5.1. Participant Biometrics

MFA – intervention participants showed no differences in the biometrics recorded, pre and post intervention. The same was true for the MFA – control group. Navicular height was significantly greater in the EMS group in comparison to the MFA participant's pre intervention period. All other biometrics between the two groups were not statistically significantly different. In addition to this activity levels between the two groups were not significantly different from one another.

4.5.2. Pedobarographic Statistical Parametric Mapping (pSPM)

Pedobarographic statistical parametric mapping (pSPM) showed no differences between walking conditions in the MFA groups, both pre and post intervention period. pSPM results also showed no differences for the EMS group between walking barefoot and minimally shod. Additionally, no differences were found between the MFA and EMS groups while walking barefoot or minimally shod.

4.5.2.1. MFA Group Plantar Pressure Distributions

Figure 4.2 shows the average peak plantar pressures for all three walking conditions, for all of the MFA participants, pre-intervention period, once all the prints had been optimally transformed to line up with the barefoot walking average print. It can be seen that the average peak pressure prints of the barefoot and minimally shod walking conditions have similar peak pressure values and distributions, with the highest pressures prodominantly at the heel and ball of the foot. In comparison, the average peak pressure print for the conventionally shod walking condition is noticeably different. The peak pressure from the conventionally shod condition is lower. The greatest pressure in the conventionally shod condition is at the heel. However, despite appearances there are actually no statistically significant differences between the walking conditions, as can be seen the statistical analysis shown in Figure 4.3.

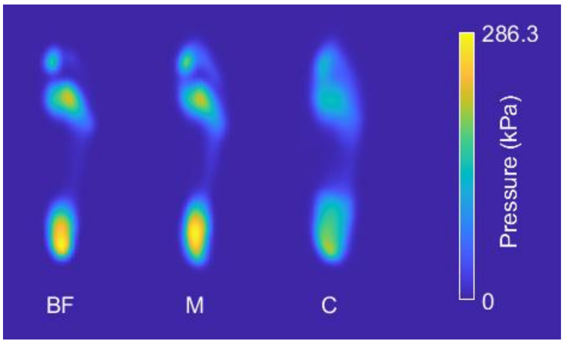

Figure 4.2: All MFA participants (n = 51), pre-intervention period average peak plantar pressures for each walking condition. Where "BF", "M" and "C" refer to barefoot, minimally shod, and conventionally shod walking respectively.

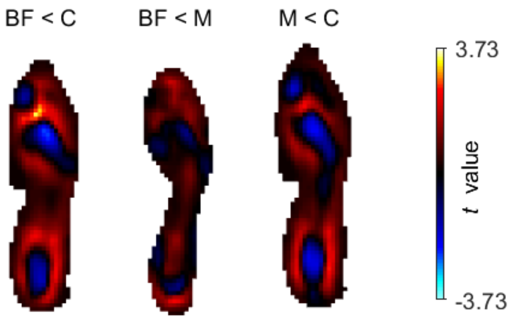

Figure 4.3: Statistical comparisons of All MFA participants, pre-intervention period (n = 51) peak pressures between different walking conditions. Where "BF", "M" and "C" refer to barefoot, minimally shod, and conventionally shod walking conditions, respectively. The statistical tests were done in pairs. Blue represents when the plantar pressures of the conditions left of the "less than" symbol is greater, and red represents the same for conditions to the right of the "less than" symbol. No statistically significant differences were found.

Figure 4.4 shows the average peak plantar pressure for all the walking conditions for the MFA – intervention participants, at the end of the intervention period. Like the prints shown in Figure 4.2, the shod conditions were optimally transformed to line up with the barefoot condition.

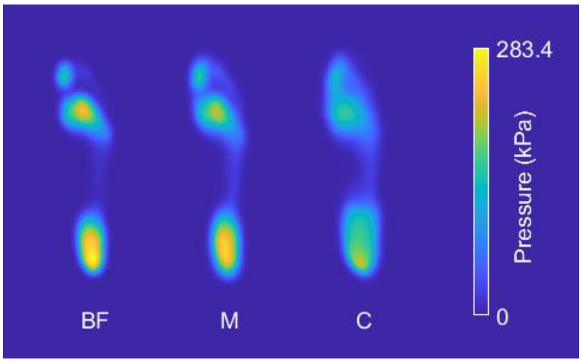

Figure 4.4: MFA – intervention participants (n = 22), post intervention period average peak plantar pressure for each walking condition. Where "BF", "M" and "C" refer to barefoot, minimally shod, and conventionally shod walking, respectively.

The average prints in Figure 4.4 are similar to the prints in Figure 4.2. The conventionally shod walking condition for the MFA – intervention participants, post-intervention period, had an average peak pressure print that has visibly lower peak pressures than the other two conditions. With both barefoot and minimally shod walking producing average peak plantar pressure prints that were very comparable. However, there was no statistically significant differences between any of the walking conditions. As shown the statistical analysis presented in Figure 4.5.

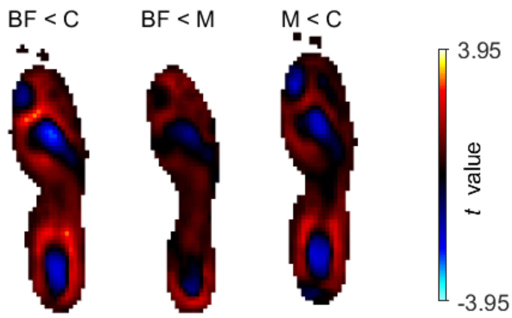

Figure 4.5: Statistical comparisons of MFA – intervention participants, post-intervention period (n = 22) peak pressures between different walking conditions. Where "BF", "M" and "C" refer to barefoot, minimally shod, and conventionally shod walking conditions, respectively. The statistical tests were done in pairs. Blue represents when the plantar pressures of the conditions left of the "less than" symbol is greater, and red represents the same for conditions to the right of the "less than" symbol. No statistically significant differences were found.

Figures from Figure 4.2 through to Figure 4.5 provide strong evidence that regular use of minimal footwear for six months has no influence on plantar pressure distribution for each condition. Figure 4.6 further cements this as the case, by directly showing no statistically significant differences pre and post intervention period for each walking for the MFA – intervention group.

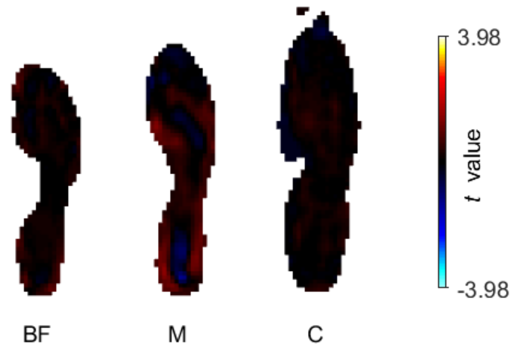

Figure 4.6: Statistical comparisons of MFA – intervention participants (n = 22) pre and post intervention period peak pressures for each walking condition. Where "BF", "M" and "C" refer to barefoot, minimally shod and conventionally shod walking conditions respectively. Blue represents when the pre-intervention period plantar pressure is greater, and red represents when the post-intervention period pressure is greater. No statistically significant differences were found.

4.5.2.2. EMS Group Plantar Pressure Distributions

Figure 4.7 shows that plantar pressures of barefoot and minimally shod walking are not statistically significantly different from one another. Additionally, barefoot and minimally shod walking average peak pressures look very similar to one another, much like in the MFA group. Unlike the MFA group, the EMS average peak pressure prints for both barefoot and minimally shod walking have relatively higher peak pressures located at the hallux.

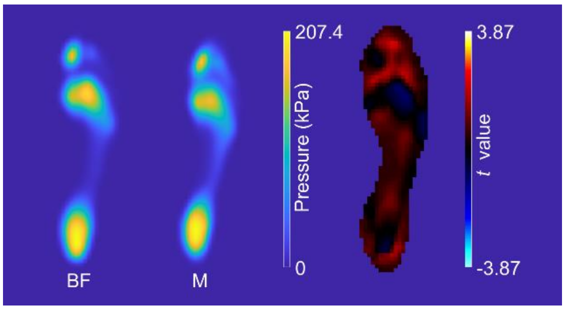

Figure 4.7: Comparison of peak pressures between all barefoot and minimally shod trials from the EMS study (6 trials per condition for each of the 20 participants). From left to right: Average total barefoot plantar pressure; Average total minimally shod pressure; Colour bar with colours reflecting absolute pressure values (kPa); Raw t

values of the statistical inference where cooler colours (blue) correspond to pixels where the minimally shod condition, pressures are higher and warmer colours (red-yellow) correspond to pixels where the barefoot condition pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05).

Figure 4.8 shows that the relatively higher pressure located at the hallux in the EMS group is not significantly greater than the MFA group. In fact, it shows that EMS peak plantar pressure was not even trending towards higher pressures than the MFA group. It was the MFA that higher pressures trending at the heel. Of course, overall, there was no statistically significant differences between any of the walking conditions between the two groups.

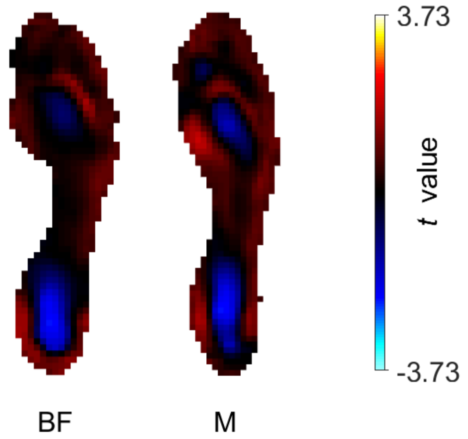

Figure 4.8: Statistical comparison between the MFA (n = 51) and EMS (n = 20) groups, for both barefoot and minimally shod walking conditions. Where "BF" and "M" refer to barefoot and minimally shod walking conditions, respectively. Blue represents when the pre-intervention period plantar pressure is greater, and red represents when the post-intervention period pressure is greater. No statistically significant differences were found.

4.5.3. 2D Centre of Pressure (2D-CoP)

2D – CoP trajectories were calculated for each condition once all the 3D plantar pressure records had been aligned to one another via optimal transformations. The average of these 2D – CoP trajectories along with the average peak pressure prints (taken from the pSPM analysis) were optimally transformed as can be seen in Figure 4.9.

4.5.3.1. MFA Group 2D Centre of Pressure (2D-CoP)

2D-CoP trajectories revealed differences between all walking conditions in the MFA group before the invention period. MFA – intervention participants showed no differences in their 2D-CoP trajectories pre and post the intervention period within conditions.

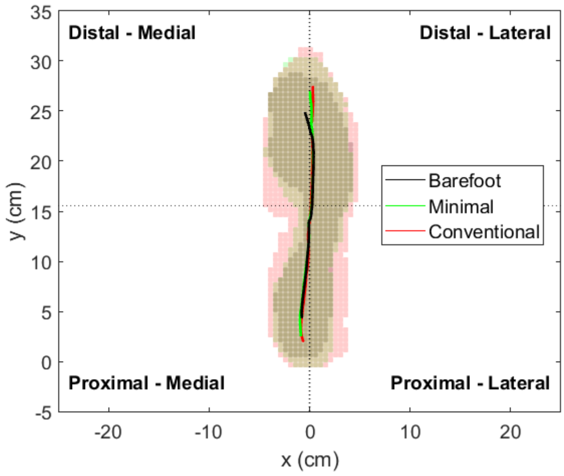

Figure 4.9: All MFA participants, pre-intervention 2D-CoP trajectories. The shaded regions depict the average peak pressure prints of the three conditions (with the minimally and conventionally shod average peak pressure prints aligned via optimal transformations to the barefoot average print). The mean centre of pressure trajectories for each condition (derived from all of the optimally transformed 3D plantar pressure records), overlay their respective average peak pressure prints.

It can be seen in Figure 4.9 that the barefoot CoP trajectory is shorter in the proximal – distal direction than both the CoP trajectories of the shod conditions. It starts more distally and ends more proximally than either shod condition. In addition to this, the barefoot CoP trajectory ends more medially than the shod conditions CoP trajectories.

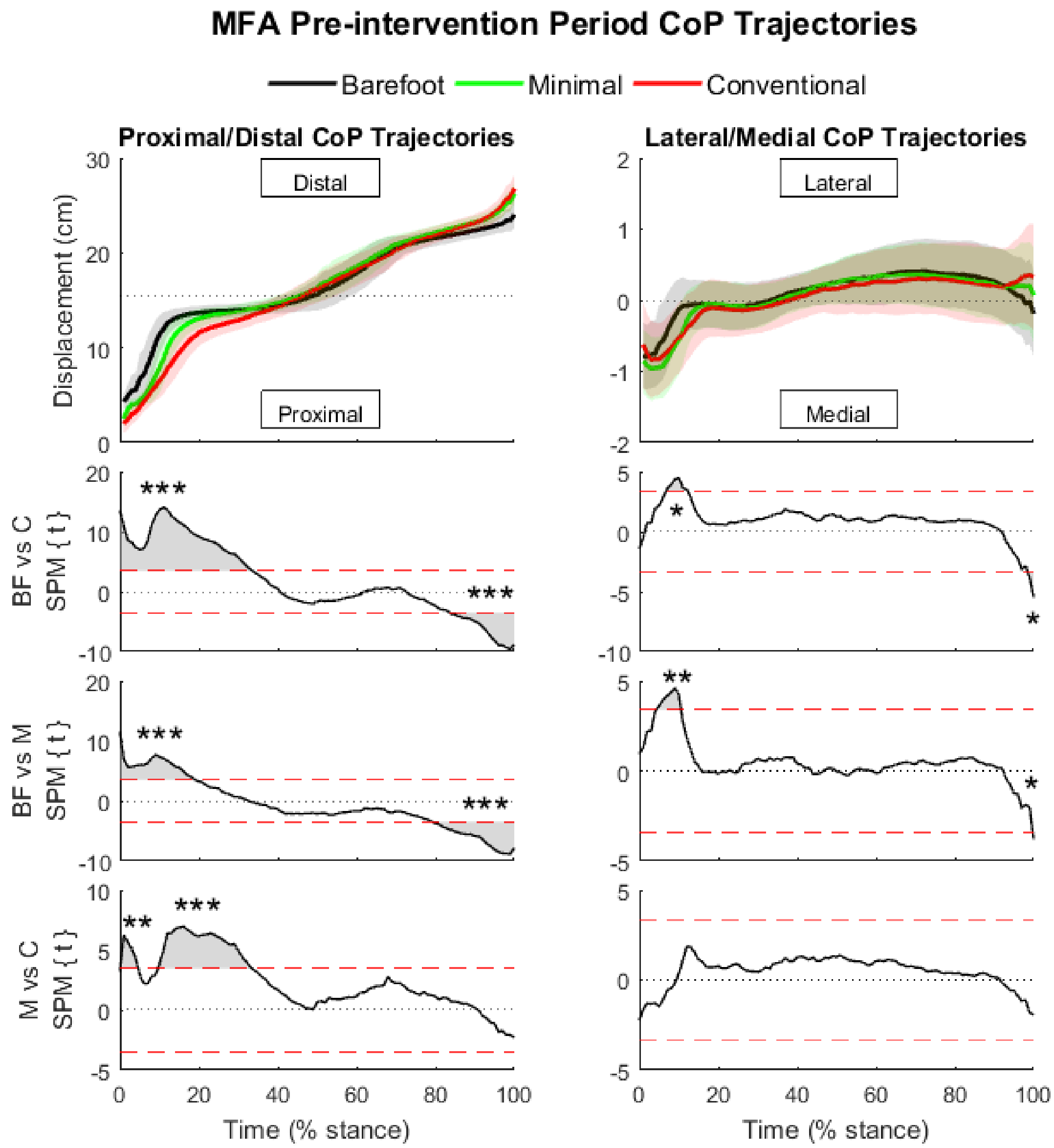

Figure 4.10: MFA group (n = 51) pre-intervention period, proximal-distal and medial/lateral CoP trajectory comparisons between the three walking conditions 1D statistical parametric mapping are shown for each condition. Where "BF", "M" and "C" represent barefoot, minimally shod, and conventionally shod walking respectively. Paired t-test with Bonferroni correction was the statistical test employed for each comparison. Shaded regions correspond to the period of stance where two CoP trajectories are statistically significant from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

Figure 4.10 shows that the barefoot walking proximal – distal CoP trajectory starts and ends more distal and proximal, respectively, than both shod conditions. At initial contact barefoot walking CoP is most distal at 4.34 ± 0.81cm from the aligned space ($p<0.001$ when compared with both shod walking conditions), and the conventionally shod condition was the most proximal at 1.98 ± 0.95cm with the minimally shod condition a significant intermediate between the two other condition at 1.98 ± 0.95cm ($p<0.005$ when compared to the conventionally shod condition). Overall, the proximal – distal CoP trajectories reveal that the minimally shod condition is an intermediate between the barefoot and conventionally shod conditions. Lateral/ Medial CoP trajectories do exhibit statistically significant differences between the shod conditions versus the barefoot condition, however differences are no more than a couple of millimeters in size and are therefore unlikely to influence different musculoskeletal responses. This is because a few millimeters difference in medial lateral displacement is not likely to have a meaningful difference on moments produced that are acting in that dimension. However, no research has quantified the threshold for medial/lateral CoP displacement thresholds influence on moment arms and would be an interesting area for future studies. It can also be seen that there is no statistically significant difference between the shod conditions lateral/medial CoP trajectories.

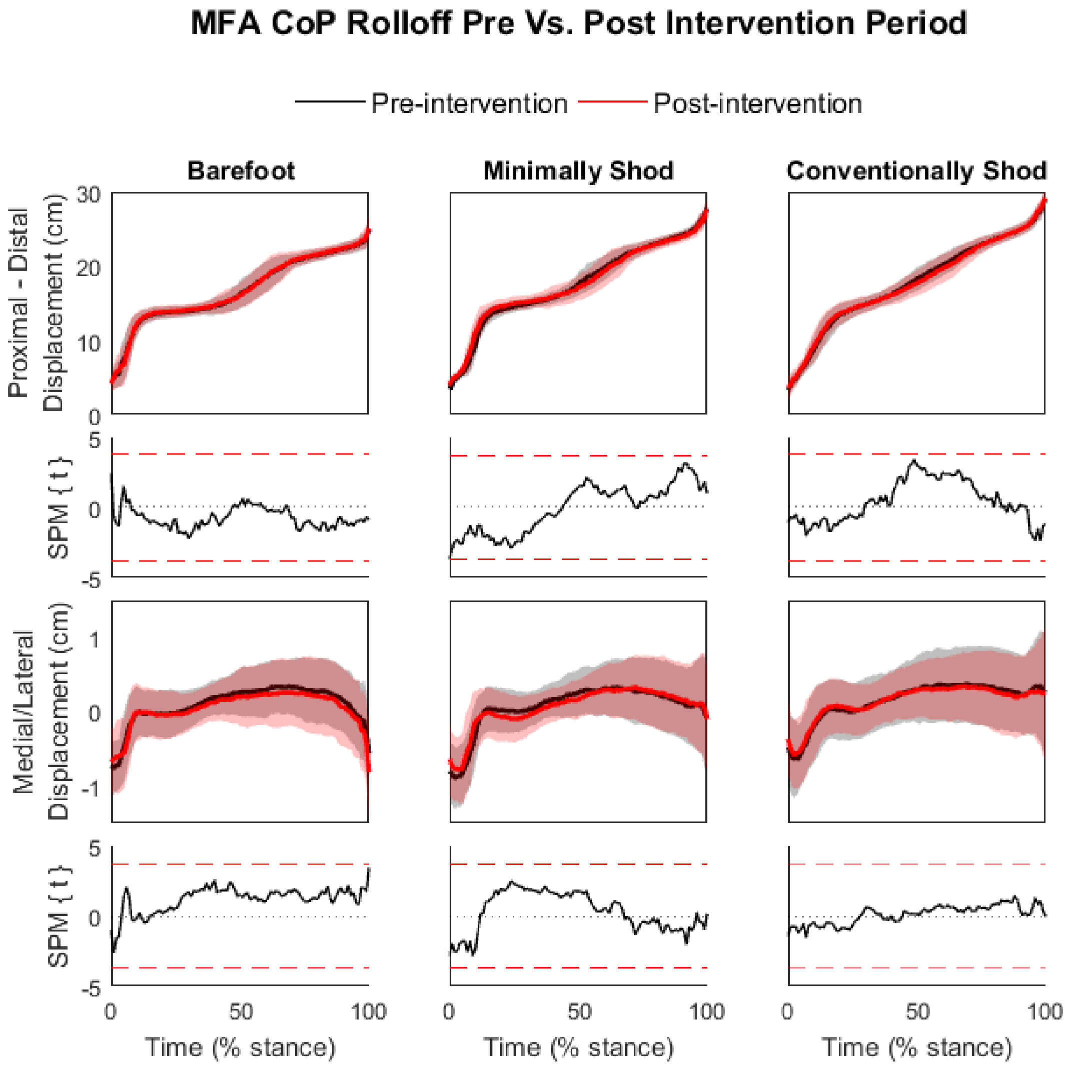

Figure 4.11: MFA-intervention group (n = 22) proximal-distal and medial/lateral CoP trajectory comparisons. Comparing each condition's pre and post intervention period walking trials. Paired t-tests 1D – SPM plots detail statistically significant differences between comparisons are directly below their respective comparisons. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

Figure 4.11 shows that six months of regular minimal footwear use for the MFA intervention group caused no changes in CoP distribution in any of the walking conditions.

4.5.3.2. EMS Group 2D Centre of Pressure (2D-CoP)

2D – CoP trajectories of EMS walking barefoot as well as minimally shod were found to be comparable to those of the MFA group.

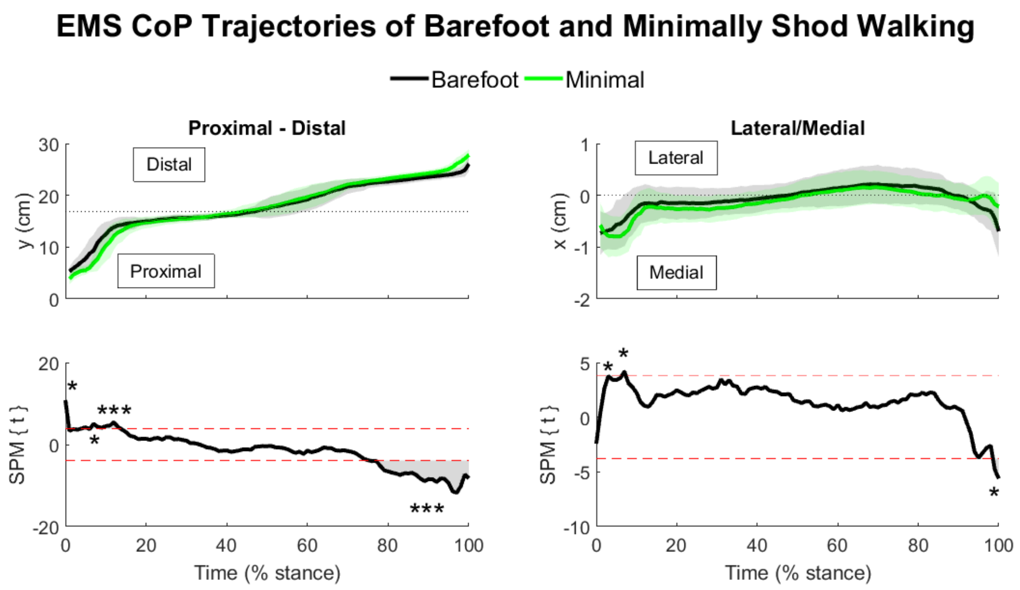

Figure 4.12: EMS (n = 20) proximal-distal and medial/lateral CoP trajectory comparisons. Comparing minimally shod walking to barefoot walking. Paired t-tests 1D – SPM plots detail statistically significant differences between comparisons are directly below their respective comparisons. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

Figure 4.12 shows the proximal – distal CoP trajectory of barefoot walking to start statistically significantly more distal (5.31 ± 0.75cm, $p<0.05$) than the minimally shod condition (3.86 ± 1.04cm), and finish statistically significantly more proximal, mirroring the results from MFA study. The Lateral/Medial CoP trajectories do reveal statistically significant differences between the two tested conditions but as these differences are so small and are therefore unlikely to influence different musculoskeletal responses. This is because a few millimeters difference in medial lateral displacement is not likely to have a meaningful difference on moments produced that are acting in that dimension. However, no research has quantified the threshold for medial/lateral CoP displacement thresholds influence on moment arms and would be an interesting area for future studies.

4.6. Discussion

The first hypothesis, minimally shod walking peak plantar pressure will be less than barefoot walking and greater than conventionally shod walking was rejected. Plantar pressure distributions between all three conditions were not statistically significantly different from one another (Figure 1.3), despite average peak pressure distributions being clearly visibly different between conditions (Figure 4.2). This result is in contrast with findings from Carl and Barrett (2008), who found peak pressures to be higher in barefoot walking when compared to walking in either flip-flops or athletic footwear. This could be because they used pressure sensitive insoles to record the measurements as opposed to using a pressure plate as was the case with this study.

All pSPM analysis employed during this study revealed no statistically significant differences. No differences were found between barefoot, minimally shod, and conventionally shod walking for the MFA participants, pre-intervention period. This suggests that plantar pressure distribution does not change for walking in any given type of footwear, or while barefoot, for a conventionally western shod population. No differences were found between the walking conditions in both the MFA control and intervention groups at the end of intervention period. This suggests that regular use of minimal footwear has no influence on peak plantar pressure distributions. No differences were found between barefoot and minimally shod walking for the EMS participants. This finding is in line with the second hypothesis of this chapter but seems rather meaningless given that conventionally western shod, conventionally shod walkers produce peak plantar pressure distributions that are not significantly different from them walking barefoot. There were even no statistically significant differences between the MFA and EMS groups when walking barefoot and minimally shod. This suggests that additional experience in minimal footwear still has no influence on spatial plantar pressure distributions. The results also suggest that EMS spatial plantar pressure distributions would not change even if they wore conventional footwear. These results were surprising and contradicted many of our hypotheses.

D'Août et al. (2009) found statistically significant differences in peak plantar pressure distributions between conventionally western shod participants from Belgium, shod Indians (wore mainly sandals/flip-flops outside and barefoot inside the house) and habitually barefoot Indians, when walking barefoot. This suggests that experience in different walking conditions leads to different peak plantar pressure distributions for barefoot walking. However, the present study found this not to be the case. There are, however, some key differences between this present study and the one conducted by D'Août et al. (2009). One such difference is the level of walking experience in a group's accustomed walking condition. Habitually barefoot walkers have walked barefoot all their lives, which is far greater than the six months and two and a half years of minimal footwear use of the MFA and EMS groups, respectively, in the present study. Therefore, it may be the case that experience in minimal footwear use may have an effect on peak plantar pressure distributions, but more time regularly using a footwear condition is required to cause the differences. Another point of interest comes from a key finding in the D'Août et al. (2009) study, that barefoot walkers have wider feet and more equally distributed peak pressures. The relative foot width of all groups in that study were significantly different from one another whereas foot width for MFA participants, pre-intervention period, MFA-intervention participants, post intervention period and EMS participants all had comparable foot widths (MFA and EMS foot width results in thesis chapter three). Therefore, it could be foot width that causes the changes in peak plantar pressure distributions. Ashizawa et al. (1997) showed habitual barefoot walking leads to wider feet when done from childhood. Finally, the sample size of the groups is much greater in the D'Août et al. (2009) study. They had 70 barefoot Indians, 137 shod Indians, and 48 conventionally shod Europeans. Given the smaller sample sizes in the present study, we postulate that the variation between individual peak pressure distributions outweighed any differences caused by the walking conditions. As a result, peak plantar pressure distribution differences between barefoot, minimally shod, and conventionally shod walking for healthy conventionally shod adults may be discoverable with greater sample sizes. Future studies should employ pSPM analysis on larger groups of habitually conventionally western adults, comparing barefoot, minimally shod, and conventionally shod walking.

2D – CoP trajectories proved to be a more robust analysis metric than the peak plantar pressure distributions. Proximal to distal CoP trajectories revealed temporal differences between all walking conditions in both MFA and EMS groups. Overall, the results showed minimally shod walking to be an intermediate between barefoot and conventionally shod walking for MFA participants at the start of the study.

In line with our third hypothesis, proximal to distal CoP trajectories during heel strike and loading response were the most distal when walking barefoot and most proximal when walking conventionally shod, with the minimally shod walking CoP trajectories being a significant intermediate during this stance period. Barefoot walking proximal to distal CoP trajectories were also more proximal at toe-off when compared to the shod walking conditions. Furthermore, the proximal to distal CoP trajectories for barefoot walking in both MFA and EMS groups progress distally at the greatest rate during the initial loading response when compared to the other walking conditions. This means that heel to ground contact area is increased at the greatest rate when walking barefoot, most likely to distribute the load experienced at heel strike over the largest surface area possible as quickly as possible in order to reduce the pressure experienced on the bare foot. However, these differences could also be caused by differences in walking speed. The average walking speed for the MFA participants, pre-intervention period are 1.49 ± 0.17, 1.50 ± 0.17, and 1.53 ± 0.17 metres per second for barefoot, minimally shod and conventionally shod walking, respectively. However, statistical analysis comparing walking speed between conditions revealed no statistically significant differences (results in chapter five). In addition to this, the proximal to distal CoP trajectory differences between walking conditions do not correspond to the proximal to distal CoP trajectory differences between the fast and slow barefoot walking velocities observed by Pataky et al. (2014). This strongly suggests that the differences observed in this study between barefoot, minimally shod, and conventionally shod walking are the result of footwear's influence on CoP distribution as opposed to walking speed.

Overall, the shod walking conditions was found to have a significantly higher proximal to distal CoP trajectory range than barefoot walking for the MFA group. This could be caused by the additional length footwear provides around a foot, shown in Figure 4.9.

No differences were found within walking conditions for the MFA intervention group, pre and post intervention period. Therefore, our fourth hypothesis was rejected: Regular use of minimal footwear for six months does not alter heel-to-toe progression during stance phase during walking beyond the initial introduction of the footwear. In addition to this, minimally shod walking CoP trajectories from the MFA and EMS groups are comparable, meaning that regular use of minimal footwear for longer time periods do not elicit any stance phase changes on heel to toe transition based on experience either. In addition to this, there were no changes to either barefoot or conventionally shod walking CoP trajectories pre and post intervention period. Therefore, regular use of minimal footwear for a six-month period has no influence on either barefoot or conventionally shod walking. EMS and MFA barefoot CoP trajectories were comparable, suggesting regular use of minimal footwear beyond six months has no influence on minimally shod or barefoot walking foot kinematics either. From this evidence we concluded that all stance phase changes as a result of minimal footwear are immediate, and that regular use of minimal footwear has no influence on either barefoot or conventionally western shod walking for healthy conventionally shod adults. This is different to running in minimal footwear, where minimally shod runners went from 30% to 80% forefoot strike pattern and significantly reduced heel pressure after a four-week familiarisation period (Warne et al., 2014). This is likely because mechanical stresses on the foot are greater during running so the foot must adapt. It should also be noted that the EMS group have only been wearing minimal footwear for two and a half years on a regular basis. Experienced based gait differences from wearing minimal footwear may arise if conventionally western shod adults are given even more time to regularly wear minimal footwear. Potential differences may have been found by using a new analysis technique, STAPP (spatiotemporal analysis of plantar pressure measurements using statistical parametric mapping), which does not subsample the data at all (Booth et al., 2018).

The MFA and EMS barefoot and shod average peak pressure prints from the pSPM analyses are key to the alignment of all the prints within each condition to make the 2D – CoP analysis possible. They are also used to define proximal to distal and medial/lateral divisions shown in all the CoP results within this study. However, this proved challenging, as although these reference prints are aligned to one another, size and shape differences exist between these reference prints. In order to overcome this challenge, the vertical and horizontal centroids for each reference print was taken and average vertical and horizontal centroids calculated to be used for the medial/lateral and proximal/distal division lines, respectively, for both the MFA and EMS groups. This proved successful as the differences between centroid values of all references prints (within a group) were very close to start with. Using the MFA group as an example, standard deviations of 0.04cm and 0.37cm were found for the average medial/lateral and proximal to distal centroid division lines, respectively. An indication that despite shape and size differences between reference prints, alignment has been reached between the prints. However, there is no guarantee that there is good anatomical alignment, and this point is discussed further in the limitations section of this chapter.

Another point of interest is that shod walking medial/lateral CoP exhibits lateral CoP at heel strike (Zhang et al., 2017), however shod walking CoP in the present study is medial at heel strike for both the MFA and EMS group. This is likely because the present study used a pressure mat that records the CoP of the shoe sole whereas Zhang et al. (2017) uses pressure sensitive insoles that recorded the CoP of the sole of the foot while shod. To prove these differences are caused by differences in measuring equipment and potentially find other plantar differences between insole and pressure mat shod walking a simultaneous recording of pressure data using a pressure plate and an insole system should be conducted.

The peak plantar pressures of EMS group (Figure 4.7) are lower than the plantar pressures of the MFA group, pre-intervention period (Figure 4.2). A finding partially supported by research from D'Août et al. (2009), who found habitually barefoot walkers to have lower peak plantar pressures. This finding was attributed to habitually barefoot walkers having wider feet and smoother stance phases resulting in more equally distributed plantar pressures (D'Août et al., 2009). In the present study however, foot size was not significantly different between the groups.

Additionally, barefoot and minimally shod walking CoP trajectories are comparable between the EMS (Figure 4.12) and MFA (Figure 4.10) groups, suggesting that EMS participants do not distribute load any differently to MFA participants. This led us to question why peak pressure was less in the EMS group than the MFA group. We determined that EMS participants simply walked slower, distributing their load over a longer time period, thereby reducing their peak pressures – a result that is hidden in the normalised stance phase. However, comparing the 2D – CoP pressure trajectories between these two groups has its limitations. The 2D – CoP trajectories have only been optimally transformed within each population; as a result, there is no guarantee that CoP trajectories cross-population will be aligned, making any comparison between the two groups unreliable.

4.6.1. Limitations

The greatest challenge associated with the work within this chapter was attempting to compare the differently shaped pressure signatures between the three walking conditions, as a result of using a pressure plate as opposed to pressure sensitive insoles. The analysis techniques used within this chapter as well as chapter two can align and scale pressure distributions to any desired reference, however manipulating the scale of pressure distributions between intended comparisons eliminates the influence scale has on differences between those conditions. In the case of the results presented within this chapter, conventionally and minimally shod walking plantar pressure distributions were scaled to optimally overlap with the barefoot plantar pressure distributions. This removed the limitation of anatomical alignment between different walking conditions but eliminates any differences that may have existed between walking conditions as a result of scale. This is likely the reason why no differences were observed between barefoot and conventionally shod plantar pressure distributions.

To maintain the size differences between walking conditions the 2D-COP analysis within this chapter and chapter two compared optimally aligned non-scaled plantar pressure characteristics of the walking conditions. However, this also had some limitations. The main issue was the size differences between the walking conditions.

The pressure distributions produced by bare feet are smaller than the pressure distributions produced by the same feet minimally and conventionally shod. The optimal scaling transformations used to scale between walking conditions during the pSPM analysis would artificially skew the representation of heel-to-toe transition within the 2D CoP results. Therefore, scaling the shod walking conditions plantar pressures to the barefoot walking plantar pressures was omitted. These walking conditions are still comparable because the pressure experienced by the sole of the shoes is still a relevant indicator of gait characteristics while walking shod. However, there is a limitation when aligning the reference prints used to make the 2D-CoP results from the different walking conditions when they are all differently sized. There is no guarantee that the anatomical regions between walking conditions will overlap. When aligning the prints, the prints were aligned to the centroid of the average barefoot walking condition, which may not be the reality of where the foot lays inside the shoe. In addition to this, medial/lateral and proximal/distal divisions were defined about the average of the walking conditions average reference print centroid. This is one potential explanation as to why lateral heel strike was not observed in the shod conditions.

Discrete analysis of localised loads is another potential analysis technique that appears it could have been used to overcome the scaling limitation stated above. This analysis method involves predefining pressure regions based on discrete anatomical regions (e.g., Hallux, Heel, etc.) and summing up the pressures within these regions for comparisons (Bennetts et al., 2013). However, this analysis method was not incorporated into this thesis because shod walking plantar pressure distributions measured by pressure plates do not truly relate to discrete anatomical regions. The sole material of any given footwear between the pressure plate and the bare foot skews the pressure distribution of discrete anatomical regions and in many cases makes the discrete anatomical regions unrecognisable and therefore undefinable. This method could be used for shod and barefoot plantar pressure comparisons if the shod walking plantar pressure measurements were recorded by plantar pressure sensitive insoles. However, if this was the case the limitation relating to the pressure analysis techniques used with this thesis would no longer exist. In conclusion, there is no ideal analysis method for comparing shod and unshod walking plantar pressures that are recorded with a pressure plate. Future studies intending to compare barefoot, and shod walking plantar pressure results should use pressure sensitive insoles.

4.7. Conclusions

Analysis of CoP trajectories revealed differences between all the walking conditions where pSPM analysis could not. This suggests temporal differences are greater than spatial differences during stance phase for the different walking conditions. Temporal analysis found minimally shod walking to be significantly different from both barefoot and conventionally shod walking during heel strike and loading response. Yet, minimally shod walking still shared similarities to both the other walking conditions, making it an intermediate between barefoot and conventionally shod walking.

Both temporal and spatial analyses employed for this study found regular use of minimal footwear will not change minimally shod walking gait characteristics during stance phase for healthy conventionally western shod adults, regardless of the level of experience gained. Therefore, the walking gaits immediately adjust to the footwear condition and do not change for healthy adults. Future research should investigate if kinematic analysis in adults confirms the same.

These results show minimal footwear is an intermediate between barefoot and conventionally shod walking. As experience of minimally shod walking had no influence on gait while walking in minimal footwear, this study cannot explain the observed differences in gait between conventionally western shod and habitually barefoot/ minimally shod walkers observed in previous research. We can only hypothesis that gait changes occur during childhood and that future research should focus on this.

4.8. Acknowledgments

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4.9. References

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5. Chapter 5: A prospective study on the Kinematic and Kinetic Characteristics of Barefoot, Minimally Shod and Conventionally Shod Walking while Transitioning to Regular Minimally Shod Walking.

5.1. Chapter 5 Covering page

5.1.1. List of Authors

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5.1.2. Author Contributions

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Catherine Willems: Supervised and guided chapter write up.

Kristiaan D'Août: Provided supervision and guidance for all aspects of the project and chapter.

5.1.3. Chapter 5 Foreword

The differences in toe flexor strength observed in chapter three are likely to be caused by differences in kinematics and kinetics as a result of minimally shod walking. Some foot kinematic differences were observed between barefoot, minimally shod, and conventionally shod walking CoPs derived from the plantar pressure results within chapter four. However, to fully understand how minimal footwear influences gait characteristics, full lower limb kinetics and kinetics need to be performed. Therefore, this chapter evaluates barefoot, minimally shod, and conventionally shod walking kinematics and kinetics. This will also answer an aspect the first central research question: What differences exist between barefoot, minimally shod, and conventionally shod walking in healthy adults? It also evaluates the influence regularly walking in minimal footwear has on kinematics and kinetics while walking barefoot, minimally shod, and conventionally shod, in order to answer an aspect of the second central research question: Can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function? To answer both of the questions, the MFA group was utilised in this chapter as well as in chapters three and four. The MFA group had key kinematics and kinetics measured pre and post the six-month intervention period. Given that both this chapter, chapter three, and chapter four use the MFA group, there is potential for a connection to be made between kinematics and kinetics, foot strength and plantar pressure characteristics. Overall, this chapter evaluated the following hypotheses:

- Walking speed will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate.
- Six months of regular minimal footwear use will result in a reduction of walking speed while walking minimally shod.
- Stride length will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate.
- Six months of regular minimal footwear use will result in a reduction of stride length while walking minimally shod.
- Conventionally shod walking will produce a greater ankle dorsiflexion angle at initial contact than both barefoot and minimally shod walking.
- Shod walking peak ankle, knee and hip angles will be greater than barefoot walking.
- Peak ankle plantarflexion moment will be greatest while walking conventionally shod and lowest while barefoot.
- Peak power will be lowest while walking barefoot, and greatest while walking conventionally shod.
- Six months of regular minimal footwear use will lead to minimally shod walking peak ankle, knee, and hip angles tending towards those of barefoot walking.

- Six months of regular minimal footwear use will increase dynamic foot spread about the ball of the foot while walking barefoot.
- Six months of regular minimal footwear use will increase arch stiffness while walking barefoot.

5.2. Abstract

Walking in minimal footwear has been described to exhibit gait characteristics closer to barefoot walking than walking in conventional modern-day footwear, while still offering protection for the feet from the environment. However, differences in gait characteristics still exist between barefoot and minimally shod walking. The studies that have produced these findings have participants with no previous experience with minimal footwear. This study aims to firstly detail minimally shod walking gait characteristics compared to barefoot and conventionally shod walking, and secondly investigate the influence six months of regular minimally shod walking has on barefoot, minimally shod, and conventionally shod walking gait characteristics.

22 intervention and 24 control participants' kinematics and kinetics were taken while walking barefoot, minimally shod and conventionally shod, pre and post a six-month intervention period, where intervention participants wore minimal footwear for the entire intervention period. The kinematics and kinetics taken were key spatial-temporal variables, ankle, knee and hip angles, angular velocities, moments, and powers while walking barefoot, minimally shod and conventionally shod. Key foot kinematics were also taken during barefoot walking.

Minimally shod walking spatial-temporal variables were similar to both barefoot and conventionally shod walking, pre-intervention period. Post-intervention period, intervention group minimally shod walking speed and stride width reduced by 3.16% ($p = 0.042$) and 6.23% ($p = 0.007$) respectively. Barefoot and conventionally shod walking stride width also reduced by 7.64% ($p < 0.001$) and 4.57% ($p = 0.042$) respectively. Lower limb joint kinematics and kinetics are similar between all walking conditions pre-intervention period, however differences between the walking conditions throughout the lower limb joint kinematic and kinetic results

indicate minimally shod walking as an intermediate between barefoot and conventionally shod walking. Intervention group minimally shod walking lower limb joint kinematics show changes that tend towards barefoot gait characteristics post-intervention period. However minimally shod walking remained a unique and intermediate walking condition between barefoot and conventionally shod walking. Intervention group foot kinematics were similar pre and post intervention period; no changes in foot compliance were found.

5.3. Introduction

Humans have evolved to be bipedal beings which puts additional load on the lower limbs. Hominins evolved a series of anatomical adaptations that make *Homo sapiens* specialised to bipedal locomotion (Bramble and Lieberman, 2004). For the majority of time, we, as modern *Homo sapiens* have walked and ran barefoot, with footwear believed to be invented 40,000 years ago (Trinkaus, 2005) out of the 200,000 years of our history as anatomically modern *Homo sapiens* (McDougall et al., 2005). This early footwear was very minimal in construction, it had a loose fit and no cushioning in the sole. In fact, it has only been in the last 50 years that complex support mechanisms have been incorporated into the modern footwear we are accustomed to in the present day (Shawcross, 2014, Shorten, 2000, Cavanagh, 1980, Lieberman, 2012). It is therefore clear that the rate of change to the mechanical properties of footwear outweighs any evolutionary adaption to them. As a result, footwear is an item of contention as to whether it is a beneficial tool we have invented to aid gait, much like glasses to aid our vision, or if they do more harm than good.

Studies have found that some cushioned footwear specialised for running increases running economy (Fuller et al., 2015, Hoogkamer et al., 2018), Lafortune and colleagues argued that cushioned footwear was important to reduce the impact at heel strike during walking (Lafortune and Hennig, 1992). Yet, habitually barefoot and/or minimally shod communities have consistently been shown to have fewer foot pathologies (Shulman, 1949, Hoffmann, 1905, Sim-Fook and Hodgson, 1958). These studies are old and recent research on footwear wearing habits on foot pathologies are limited. However, more recent studies have suggested that habitual use of footwear can cause pathological changes (Zipfel and Berger, 2007, Yan et al., 2013). Habitually barefoot communities have less instances of flat foot (Rao and Joseph, 1992, Echarri and Forriol, 2003). Flat foot is characterised by a particularly low longitudinal arch height (Mosca, 2010) and/or stiffness during walking (DeSilva and Gill, 2013, Saraswat et al., 2014). Yet the current literature on the influence of habitual footwear use on foot stiffness is conflicting. Holowka et al. found indigenously minimally shod participants' longitudinal arch stiffness to be greater than habitually conventionally western shod participants', whereas Kadambande et al. (2006) found habitually barefoot and/or minimally shod feet are more compliant than habitually conventionally western shod feet. These studies compare participants from western to non-western cultures. Different populations can have biomechanical differences caused by cultural and dietary variations. Habitually barefoot western communities are too scarce to perform studies to validate if the influence of western footwear wearing habits cause western foot pathologies. However, there has been a rise in popularity of minimalist footwear in western communities (Davis, 2014). These shoes are designed to simulate barefoot walking while still providing protection from the outside environment. They are officially defined as "Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices" (Sinclair et al., 2013).

Several studies have already shown the influence of minimal footwear in the literature. Minimal footwear has been shown to improve walking stability (Cudejko et al., 2020, Petersen et al., 2020) and increase intrinsic foot muscle strength (Ridge et al., 2019). The findings within the third chapter of this present thesis also found walking in minimal footwear increases foot strength. However, the current literature on minimally shod walking gait characteristics is limited.

Kinematics and kinetics have developed into a successful method to comprehend gait biomechanics (Winter, 1991). It has proved a useful tool for understanding the influence footwear has on gait biomechanics. Liebermann and colleagues showed collision forces are typically lower while running barefoot versus conventionally shod runners (Lieberman et al., 2010). Kinematics and kinetics have also been used to show the influence of footwear during walking. Spatial-temporal variables have shown barefoot walking to be slower and have reduced stride length when compared to conventionally shod walking (Wirth et al., 2011, Moreno-Hernández et al., 2010, Lythgo et al., 2009). Walking in high heels have been shown to exhibit detrimental gait characteristics such as prolonging the knee flexor moments in comparison to barefoot walking (Kerrigan et al., 2001, Kerrigan et al., 1998). Even walking in conventional footwear with cushioned heels and some form of arch support can have harmful kinetic effects on gait, including increased knee varus moments when compared to barefoot walking (Keenan et al., 2011). There are even a few studies that have investigated the kinematics and kinetics of partially minimal sandals and flip flops (Zhang et al., 2013, Chard et al., 2013, Wallace et al., 2018), and specialised minimal footwear (Wolf et al., 2008, Wallace et al., 2018, Willems et al., 2017, Petersen et al., 2020). A systematic review by Franklin and colleagues determined minimally shod walking to exhibit gait characteristics closer to barefoot walking than conventionally shod walking based on the findings within several studies (Franklin et al., 2015). Yet the current literature directly comparing the gait characteristics between barefoot, minimally shod and conventionally shod walking is limited. Wolf et al. is the only study to have done this thus far (Wolf et al., 2008). The study used the Heidelberg foot measurement method (Simon et al., 2006) to generate foot kinematics for barefoot, minimally shod, and conventionally shod walking. Wolf and colleagues found that minimally shod walking foot kinematics are more similar to conventionally shod walking foot kinematics than barefoot walking, with only the dynamic foot spread about the ball of the foot throughout the gait cycle being significantly greater while minimally shod walking when compared to conventionally shod walking, out of all the foot kinematic variables reported (Wolf et al., 2008). Currently there are no studies investigating the influence of minimal footwear on total lower limb kinematics. In addition to this, the current literature is limited on the long-term effects of walking barefoot with regards to gait biomechanics (Hollander et al., 2017b). This is important because gait characteristic differences exist between habitually barefoot walkers and conventionally western shod walkers while both groups walk in minimal footwear, suggesting experience in minimal footwear has an important influence on gait characteristics.

This study aims to firstly discover whether minimally shod walking is similar to barefoot walking, or to other types of shod walking (or in-between), and secondly investigate the influence of six months of regular minimally shod walking on minimally shod walking gait characteristics. This chapter is divided by three research questions to make it more manageable. Each research question is also supported by hypotheses:

1. What differences exist between barefoot, minimally shod, and conventionally shod walking on spatial-temporal variables and how do these variables change after six months of minimal footwear use for each walking condition?
   - 1.1. Walking speed will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate.
   - 1.2. Six months of regular minimal footwear use will result in a reduction of walking speed while walking minimally shod.
   - 1.3. Stride length will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate.
   - 1.4. Six months of regular minimal footwear use will result in a reduction of stride length while walking minimally shod.
2. What differences exist between barefoot, minimally shod, and conventionally shod walking kinematics and kinetics of the lower limb joints and how do the kinematics and kinetics change after six months of minimal footwear use for each walking condition?
   - 2.1. Conventionally shod walking will produce a greater ankle dorsiflexion angle at initial contact than both barefoot and minimally shod walking.
   - 2.2. Shod walking peak ankle, knee and hip angles will be greater than barefoot walking.

2.3. Peak ankle plantarflexion moment will be greatest while walking conventionally shod and lowest while barefoot.

2.4. Peak power will be lowest while walking barefoot, and greatest while walking conventionally shod.

2.5. Six months of regular minimal footwear use will lead to minimally shod walking peak ankle, knee, and hip angles tending towards those of barefoot walking.

3. What is the influence of six months of minimal footwear use on foot compliance while walking barefoot?

3.1. Six months of regular minimal footwear use will increase dynamic foot spread about the ball of the foot while walking barefoot.

3.2. Six months of regular minimal footwear use will increase arch stiffness while walking barefoot.

5.4. Methods

5.4.1. Experimental Procedure

51 participants (30 male, 21 female; age 27.6 ± 6.9yrs; BMI 23.6 ±3.1) were recruited for a six month longitudinal follow-up study. Simple walking tasks were performed while barefoot, conventionally shod, and minimally shod, pre and post the six-month intervention period. Participants were allocated to control and intervention groups at the end of the pre-intervention period tests. 22 intervention (13 male, 9 female; age 27.3 ± 6.2yrs; BMI 24.1 ± 2.7) and 24 control (14 male, 10 female; age 28.9 ± 7.5yrs; BMI 22.5 ± 2.8) participants returned for the post study at the end of the six month intervention period (i.e. dropout of five participants). The post study consisted of repeating the biometric measurements, and kinematic and kinetic measurements from the initial study.

Participants from the intervention group were given minimal footwear (Vivobarefoot Stealth II), and control participants were instructed to continue to wear the footwear they most regularly wore. Both groups were required to wear their allocated footwear 70% of the time they were shod, at least six days a week, for the length of the six-month intervention period. Both control and intervention participants filled out a weekly participant activity logs to monitor footwear wearing patterns and alert the researchers of any discomfort and/or injury. The participant activity log can be found in Appendix B.

Pre and post intervention period tests were conducted at the University of Liverpool Gait Lab at the Institute of Ageing and Chronic Disease (currently: Institute of Life Course and Medical Sciences) for all participants. Before the pre-intervention period tests, participants signed the consent form and filled out a questionnaire to characterise their footwear wearing habits and general health. Both consent form and questionnaire can be found in Appendix C. The participants then changed into skin conforming shorts and vests and had their key biometrics recorded, including weight and height. 12.7mm reflective markers were then attached at key anatomical landmarks following the University of Liverpool Evolutionary Morphology and Biomechanics (EMB) whole body standard marker set which can be seen in Figure 5.1. All markers were attached by the same examiner for all participants, except for one. Markers were attached onto the footwear in the locations closest to the desired anatomical sites for the shod walking conditions. Additional smaller (7.5mm) markers were attached to the right foot following the Ghent Foot Model marker set (De Mits et al., 2012) for the barefoot walking condition (the left foot still following the EMB marker set). The Ghent foot model can be seen in Figure 5.2 and the full body marker placement for the barefoot walking condition can be seen in Figure 5.3. Each time a new condition began footwear/foot markers were removed and replaced in the same position for the next condition. This can be seen in Figure 5.4. Participants were ready for their walking trials once all the markers had been attached for a given walking condition.

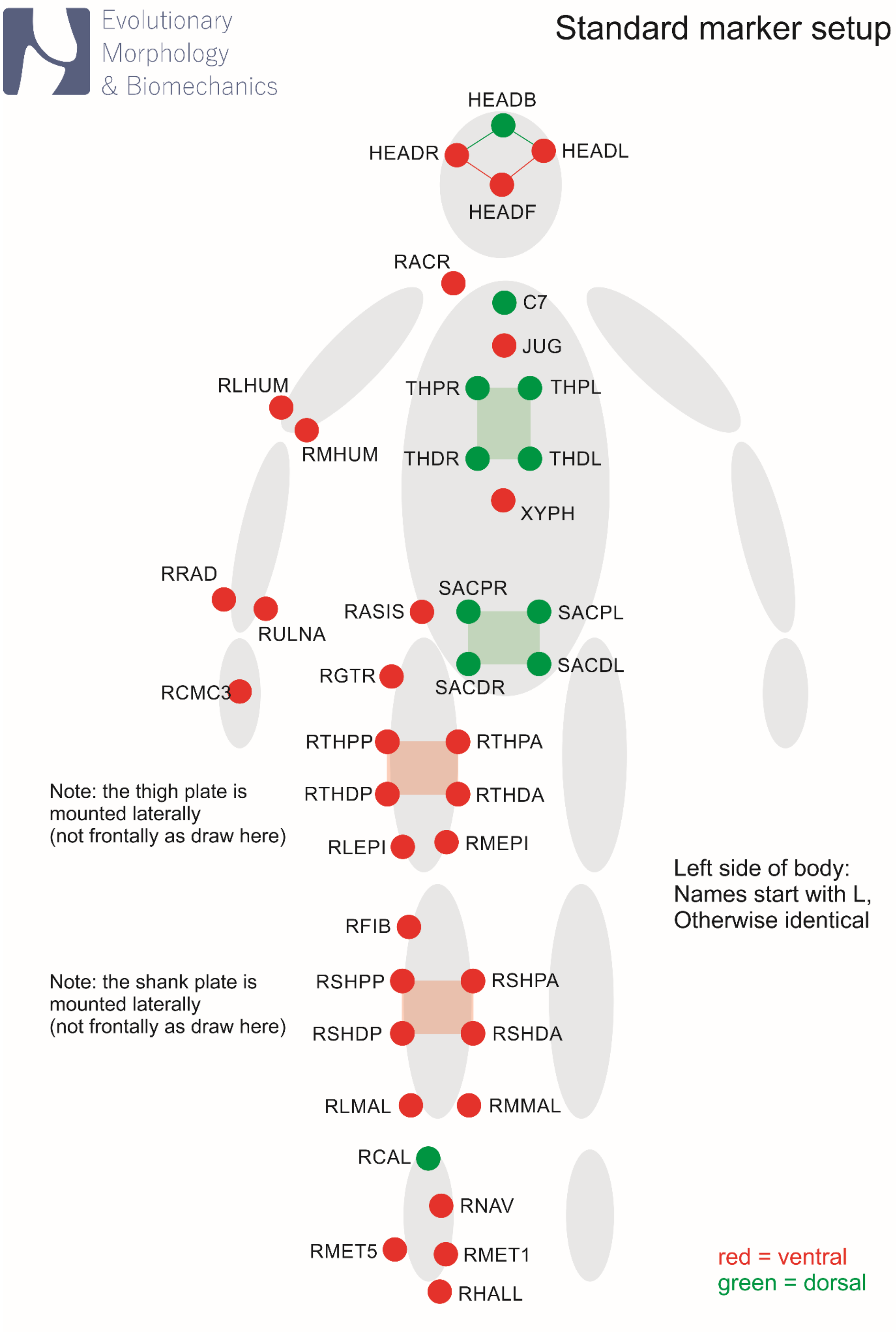

Figure 5.1: Full body EMB standard marker set. The marker names refer to key anatomical landmarks that are detailed in appendix D.

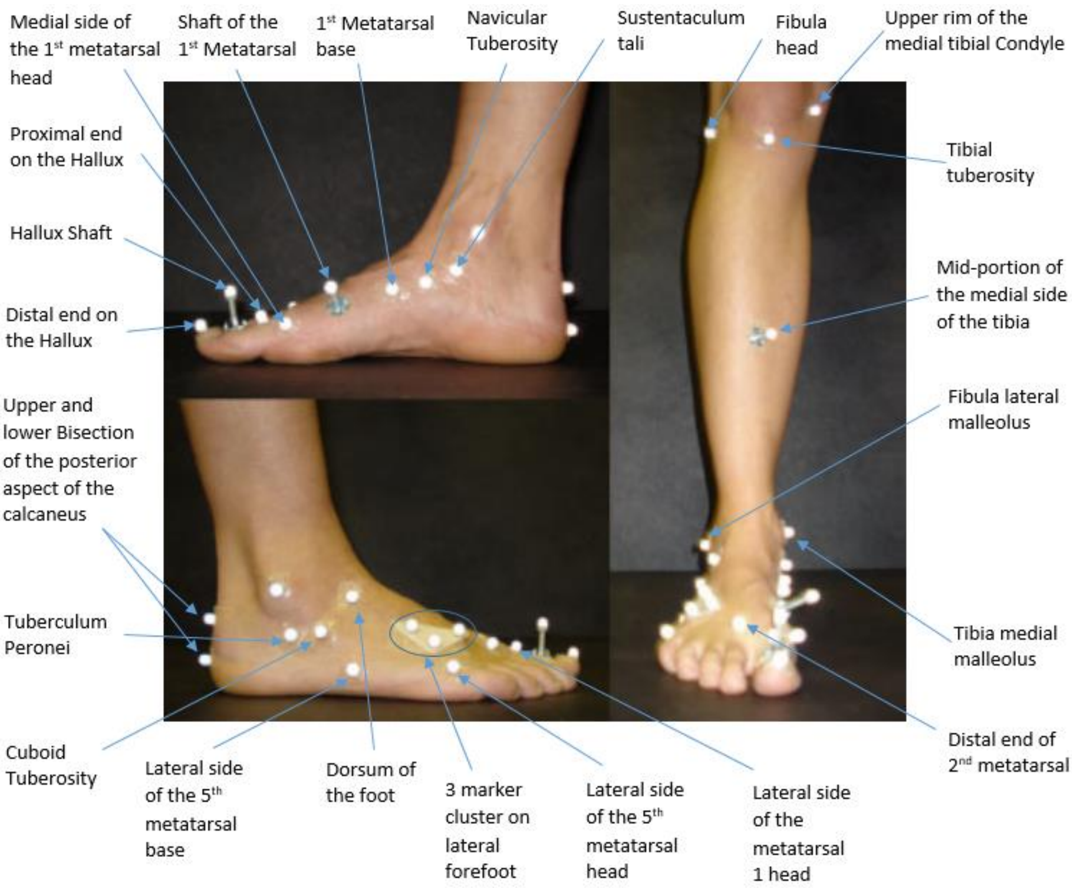

Figure 5.2: Annotated Ghent foot Model. Image taken and modified from the Ghent foot model study (De Mits et al., 2012).

Figure 5.3: Marker placement during the barefoot walking condition (Photo: D'Août).

Figure 5.4: Foot marker placement while barefoot, minimally shod and conventionally shod (from left to right. Photo: D'Août).

All walking trials were performed over ground within the gait lab. The walkway was 14m long with three Kistler force plates embedded into the ground, in series, with the first, 7.5m from the start of the walkway. Each force plate was covered with laminate rubber flooring to match the rest of gait lab and bring the height of the embedded plates in level with the rest of the floor. The volume of interest was surrounded by 12 Qualisys Oqus 7 infrared cameras (12 MP) operating at 200 Hz, controlled by Qualisys Track Manager (QTM) software.

All participants were instructed to walk down the walkway at a self-selected speed for the three different walking conditions. These walking conditions were barefoot, minimally shod, and conventionally shod. Conventionally shod walking referred to participants walking in their own most frequently worn footwear. Minimally shod walking required all the participants to walk in Vivobarefoot Stealth II shoes (that were supplied to them during the tests). Each condition required five "good" walking trials. A trial was deemed good if the walk felt natural to the participant, the participant's right foot landed within the borders of the first Kistler force plate, and there was no obvious plate targeting or acceleration. Participants had as many practice attempts as they wished prior to recording trials until they felt comfortable with the exercise. The participant could start at any of the 10cm marked intervals within the first meter of the walkway. A static trial in the anatomical position was also recorded for each condition while participants distributed their bodyweight equally between their legs. Bohannon et al. has shown healthy adults can balance their bodyweight equally between their legs with an average error between of 2.4 –

6.6% (Bohannon and Kelly, 1991). Condition order was randomised using the online services available at “randomizer.org”.

All data was collected in the gait lab at the University of Liverpool under ethics granted by the University of Liverpool Health and Life Sciences Research Ethics Committee (Human participants, tissues and databases), reference number 1911.

5.4.2. Data Analysis

The results in this study were divided into three different sections: the spatial-temporal variables; the kinematics and kinetics of the ankle, knee and hip (lower limb joints); and the foot kinematics. Each section was designed to directly assess one of the introduction questions. The data analysis required slightly different analysis approaches and these differences are discussed separately. However much of the data analysis was the same for all the results within this chapter. These similarities are discussed below.

The positions of the kinematic markers were recorded by the cameras for all walking and static trials in the study. Qualisys Track Manager 2014 (QTM) was used to assign the markers to their respective anatomical references, following the EMB marker set and Ghent Foot Model (Appendix D). These files were then exported as C3D files to be analysed in Visual 3D (C-motion).

Workspaces were made per participant in Visual 3D so that each workspace contained all the participant’s walking and static trials, for all three conditions, for both the initial and post-tests. Full body multi-segmented models were constructed with the static trials. These models were applied to their respective walking condition trials. Trials with missing anatomical markers had artificial landmarks created within Visual3D as a substitute. These substitute markers were positioned using anatomical knowledge of landmark position. Sometimes it was not feasible to substitute in landmarks and in these situations the trial was discarded. In rare circumstances entire conditions had to be discarded thereby reducing the number of conditions to compare in the analysis.

The marker positions were filtered with a low-pass, zero phase-shift 2nd order 10Hz Butterworth filter. The force data was filtered with a low-pass 2nd order 50Hz Butterworth filter. At this point gait events were defined. Kinematic gait events were generated via an automatic coordinate-based algorithm that used foot positions relative to the pelvis (Zeni Jr et al., 2008). These gait events defined heel strike and toe off for both left and right feet, for the entire length of a trial. All these gait events were manually checked to ensure accuracy. Further analysis was different for the spatial-temporal variables; the kinematics and kinetics of the ankle, knee and hip (lower limb joints); and the foot kinematics. The analysis methods for these results sections are outlined separately below.

5.4.3. Spatial-temporal Variables

The spatial-temporal variables were generated in Visual3D, exported as text files, and imported into Matlab 2017a. The spatial-temporal variables in this study focused on speed, stride width, stride length, stride frequency and duty factor (where duty factor is the ratio between the stance phase and the gait cycle). Two separate types of comparisons were made from the spatial-temporal results. The first type were comparisons between the three walking conditions for all the participants, pre-intervention period. The second type were comparison within the walking conditions, pre and post intervention period, for the intervention group and control group. The statistical analysis was performed in Matlab.

5.4.4. Lower Limb Joints Kinematics and Kinetics

The lower limb joint kinematics and kinetics required further processing in Visual 3D after the kinematic-based gait events had been generated. Firstly, kinetic-based gait events were generated using the ground reaction forces from the force plates. These gait events defined heel strike and toe off when contact was made with the force plate. Secondly, ankle, knee, and hip angles, angular velocities, moments and powers were calculated using the "Compute model-based data" function within visual 3D, via inverse dynamics (Ko and Badler, 1996). These kinematics and kinetics of the lower limb joints were then segmented and normalised to the gait events. The time taken from heel strike to the next heel strike was normalised to 0 – 100% gait cycle for the kinematic results, and the time taken from heel strike to toe-off were normalised to 0 – 100% stance phase for the kinetic results. The kinematic gait events were used for the kinematic results and the kinetic gait events were used for the kinetic results. The moment and power kinetics were normalised to body weight for each individual. These were then exported to text files and imported into Matlab 2017a.

The trials were plotted and printed into a folder for visual inspection. The trials that were deemed incorrect upon visual inspection were removed from further analysis. The force plate had not recorded ground reaction forces for eight participants (two intervention and six control), reducing the total amount of kinetic results.

For the analysis, the different intervention periods, groups, joints, walking conditions, and kinematics and kinetics were divided into different data sets. A summary of each data set and its corresponding number of participants can be seen in Table 5.1. Each dataset was calculated as follows. First, each trial was averaged to generate a single value representing a mean gait cycle for the kinematics, and a mean stance phase for the kinetics. All gait cycles and stance phases used to generate these averages were taken during steady-state gait, following previous literature (Bilney et al., 2003). Then, all trials for each participant were averaged to generate a single value per participant. Finally, data set averages were obtained by averaging the participant's means.

Table 5.1: Number of participants with at least one valid trial for the specified data set. Sets include the ankle, knee and hip kinematics and kinetics, for pre and post intervention period, for both control and intervention groups, for all three walking conditions. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod respectively. The number of participants with valid trials is constant between the majority of lower limb joints, there is one exception where pre-intervention period intervention group ankle powers have one fewer participant with valid trials than its respective lower limb joint data sets.

Data Sets – Time Period/Group /Joint/Walking Condition	No. of Participants with Valid Kinematics and Kinetics Trials		
	Kinematics	Moment	Power
Pre-intervention – Intervention Group – Ankle – B	24	23	23
Pre-intervention – Intervention Group – Hip – B	24	23	23
Pre-intervention – Intervention Group – Knee – B	24	23	23
Pre-intervention – Intervention Group – Ankle – C	25	22	22
Pre-intervention – Intervention Group – Hip – C	25	22	23
Pre-intervention – Intervention Group – Knee – C	25	22	23
Pre-intervention– Intervention Group – Ankle – M	25	23	23
Pre-intervention – Intervention Group – Hip – M	25	23	23
Pre-intervention – Intervention Group – Knee – M	25	23	23
Pre-intervention – Control Group – Ankle – B	26	19	19
Pre-intervention – Control Group – Hip – B	26	19	19
Pre-intervention – Control Group – Knee – B	26	19	19
Pre-intervention – Control Group – Ankle – C	26	19	19

Data Sets – Time Period/Group /Joint/Walking Condition	No. of Participants with Valid Kinematics and Kinetics Trials		
	Kinematics	Moment	Power
Pre-intervention – Control Group – Hip – C	26	19	19
Pre-intervention – Control Group – Knee – C	26	19	19
Pre-intervention – Control Group – Ankle – M	26	19	19
Pre-intervention – Control Group – Hip – M	26	19	19
Pre-intervention – Control Group – Knee – M	26	19	19
Post-intervention – Intervention Group – Ankle – B	22	22	22
Post-intervention – Intervention Group – Hip – B	22	22	22
Post-intervention – Intervention Group – Knee – B	22	22	22
Post-intervention – Intervention Group – Ankle – C	21	21	21
Post-intervention – Intervention Group – Hip – C	21	21	21
Post-intervention – Intervention Group – Knee – C	21	21	21
Post-intervention – Intervention Group – Ankle – M	22	22	22
Post-intervention – Intervention Group – Hip – M	22	22	22
Post-intervention – Intervention Group – Knee – M	22	22	22
Post-intervention – Control Group – Ankle – B	23	23	23
Post-intervention – Control Group – Hip – B	23	23	23

Data Sets – Time Period/Group /Joint/Walking Condition	No. of Participants with Valid Kinematics and Kinetics Trials		
	Kinematics	Moment	Power
Post-intervention – Control Group – Knee – B	23	23	23
Post-intervention – Control Group – Ankle – C	23	23	23
Post-intervention – Control Group – Hip – C	23	23	23
Post-intervention – Control Group – Knee – C	23	23	23
Post-intervention – Control Group – Ankle – M	22	22	22
Post-intervention – Control Group – Hip – M	22	22	22
Post-intervention – Control Group – Knee – M	22	22	22

The kinematics and kinetics results in this study focused on the angles, angular velocities, moments, and powers in the sagittal plane for the lower limb joints. However, all kinematics (including angular velocity) and kinetics of all three lower limb joints in all the anatomical planes can be found in Appendix E. Table 5.9 shows the naming convention used in this study for the direction of motion of the three lower limb joints, in all anatomical planes, relative to the respective full body static model. The power metrics do not conform to positive/negative direction specification. Joint power is the product of the angular velocity and moment for a given joint, therefore if both angular velocity and moment were negative for a joint at a given point in the gait cycle (indicating the negative specified direction), power would be positive, indicating the opposite and incorrect direction of the joint at that point in the gait cycle. For example, if knee flexion velocity and knee flexion moment were increasing during the stance phase, indicated as an increasing negative magnitude for both plots, knee power would appear positive on its plot. As a result, power is simply referred to as either power generation to indicate positive power or power absorption to indicate negative power.

The kinematics and kinetics results consist of: angles (Figure 5.5, Figure 5.8 and Figure 5.9), moments (Figure 5.6), and powers (Figure 5.7); each figure showing the kinematics or kinetics for the ankle, knee, and hip joints, for all the walking conditions. Differences within all kinematics and kinetics comparisons were detected with 1D statistical parametric mapping (1D-SPM), utilising common statistical tests. 1D-SPM is a topological method to compare complete time series data (Pataky, 2012).

Two types of comparisons were made from the kinematics and kinetics of the lower limb joints results. The first type were comparisons between the three walking conditions for all the participants in the pre-intervention period. Differences within these comparison types were detected by 1D-SPM utilising paired t-tests with Bonferroni corrections. Bonferroni corrections were used within Matlab to reduce the probability of a type-II error occurring because of applying t-tests to three groups. The Bonferroni corrections lead to an alpha value of 0.017. The second type of kinematic and kinetic comparisons were comparisons within walking conditions, pre and post intervention period, for both the intervention and control groups. Differences within these comparison types were detected by 1D-SPM utilising paired t-tests.

Finally, all kinematics of lower limb joints results were plotted for the duration of the entire gait cycle. Toe-off, the transition from stance to swing phase was indicated as a vertical dotted line on these plots. The average duty factor from the multiple walking conditions on each plot was taken to represent toe-off. The kinetics of the lower limb joints were plotted for the duration of stance phase.

5.4.5. Foot Kinematics

The additional markers placed on the right foot while participants were barefoot allowed us to characterise detailed foot kinematics. In order to tackle the third question of this study: what is the influence of long-term minimal footwear use on foot compliance while walking barefoot? We quantified foot compliance as the range of motion (ROM) of foot width about the ball of the foot, the longitudinal arch of the foot, and the transverse arch of the foot. Foot width ROM was defined as the maximum and minimum dynamic distance between the markers on the 1st and 5th metatarsal heads. Longitudinal arch ROM was calculated as the dynamic angle about the marker on the navicular tuberosity in relation to the upper markers on the calcaneus (bisection of the posterior aspect of the calcaneus) and 1st metatarsal head. Transverse arch ROM was calculated as the dynamic angle about the marker on the dorsum of the foot in relation to the markers on the cuboid tuberosity and navicular tuberosity.

ROM of foot width, the longitudinal arch, and the transverse arch were calculated in Visual 3D, after filtering and kinematic gait event generation. These results were exported as text files and imported into Matlab 2017a. Much like the kinematics and kinetics of the lower limb joints, the foot kinematic results were plotted and printed into a folder for visual inspection. The results were visually inspected and any results that were clearly incorrect were removed. Multiple full gait cycles of quality foot kinematics could be still found within each trial. Trial average foot kinematics were generated for each trial. All full gait cycle results of foot kinematics that were used to generate trial averages were taken within the participant's steady state gait. Participant average foot kinematics were then generated for each participant from the average trial results.

The ROM of foot width was normalised to exclude variation of foot size as a variable. Foot width ROM was normalised by dividing each participants' foot width ROM by the participants' height, as feet scale isometrically in adult humans, with foot length being approximately about 15% of stature (Atamturk and Duyar, 2008). This new term was named normalised foot width ROM. The statistical analysis was performed in Matlab.

5.5. Results

5.5.1. Spatial-temporal Variables

Table 5.2 shows the mean and standard deviations for the spatial-temporal variables of all participants pre-intervention period. Only one participant's barefoot walking spatial-temporal variables were missing as a result of technical reasons. The full data set was available for the minimally and conventionally shod walking conditions. Statistical comparisons between the walking conditions for each of these spatial-temporal variables were made. One-way ANOVA calculated statistically significant differences between walking conditions for the spatial-temporal metrics. p-values in between significant comparisons were then calculated using the appropriate post-hoc test via standard syntax built-in MATLAB. The results are shown in Table 5.3. A one-way ANCOVA with speed as a co-variant was also performed followed by the post-hoc test. These results are shown in Table 5.4. Cohen's D effect size was calculated for all significant spatial-temporal results.

The results shown in Table 5.2 reveal that barefoot walking to have the slowest walking speed, the smallest stride width and stride length, the highest stride frequency, and the lowest duty factor. Conventionally shod walking has spatial-temporal variables that tend to be the relative opposite to barefoot walking. Minimally shod walking variables are intermediate between those of barefoot and conventionally shod walking. For most spatial-temporal variables no statistically significant differences were found between the walking conditions. The only spatial-temporal metric to show a significant difference was stride length, which was 4.53% ($p = 0.032$) shorter while walking barefoot when compared to conventionally shod walking. Cohen's D effect size was calculated as 0.49 indicating a small effect size. ANCOVA with walking speed as a co-variant reveals no statistically significant difference in stride length between barefoot and conventionally shod walking. Indicating that changes in walking speed as a result of the different walking conditions, influences stride length as opposed to the walking conditions directly influencing stride length.

Table 5.2: Spatial and temporal variables of barefoot, conventionally shod and minimally shod walking for all participants, pre-intervention period. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod, respectively.

Spatial and Temporal Variables	Walking Condition		
	B (n = 50)	C (n = 51)	M (n = 51)
Speed (m/s)	1.49 ± 0.17	1.53 ± 0.18	1.50 ± 0.17
Stride Width (m)	0.119 ± 0.026	0.124 ± 0.027	0.124 ± 0.026
Stride Length (m)	1.51 ± 0.14	1.58 ± 0.16	1.55 ± 0.14
Stride Freq. (Hz)	0.992 ± 0.064	0.969 ± 0.062	0.972 ± 0.058
Duty Factor	0.648 ± 0.012	0.652 ± 0.012	0.651 ± 0.011

Table 5.3: Spatial and temporal metric comparisons between barefoot, conventionally shod, and minimally shod walking for all participants, pre-intervention period. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod, respectively. Statistical differences were detected via one way ANOVA comparisons followed by a post-hoc test. A P-values of <0.05 is represtened by "". Stride length was found to be significantly shorter while walking barefoot than conventionally shod.*

p-values from ANOVA			
Spatial – Temporal Variables	Walking Condition Comparisons		
	B vs C	B vs M	M vs C
Speed	0.54	0.96	0.7
Stride Width	0.62	0.68	0.99
Stride Length	**0.032**	0.36	0.47
Stride Frequency	0.15	0.23	0.97

p-values from ANOVA			
Duty Factor	0.15	0.34	0.89

Table 5.4: Spatial and temporal metric comparisons between barefoot, conventionally shod, and minimally shod walking for all participants, pre-intervention period. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod, respectively. Statistical factors were explored via one-way ANCOVA comparisons with speed as the co-variant. This was then followed post-hoc test. No significant differences were found.

p-values from ANCOVA (with Speed as a Covariant)			
Spatial–Temporal Variables	Walking Condition Comparisons		
	B vs C	B vs M	M vs C
Stride Width	1	1	1
Stride Length	1	0.97	0.97
Stride Freq.	0.97	0.88	0.97
Duty Factor	0.89	0.89	1

Table 5.5 shows the mean and standard deviations of the intervention group's spatial-temporal variables, pre and post intervention period for all walking conditions. The pre-intervention period spatial-temporal variables were paired to the post-intervention period variables, within the walking conditions, so that paired t-tests could be applied. Comparisons utilising paired t-tests were made within the walking conditions between pre and post intervention period tests. The results are shown in

Table 5.6. The equivalent results shown in Table 5.5 and

Table 5.6 have been made for the control participants, and can be seen in Table 5.7 and Table 5.8 respectively.

Table 5.5: Intervention group spatial and temporal variables for the intervention participants while walking barefoot, conventionally shod, and minimally shod, pre and post intervention period. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod, respectively.

Spatial – Temporal Variables	Intervention Group					
	Pre-Intervention Period			Post-Intervention Period		
	B (n=22)	C (n=21)	M (n=22)	B (n=22)	C (n=21)	M (n=22)
Speed(m/s)	1.55 ±0.15	1.6 ±0.14	1.56 ±0.13	1.52 ±0.15	1.54 ±0.16	1.51 ±0.15
Stride Width (m)	0.128 ±0.028	0.134 ±0.027	0.131 ±0.025	0.117 ±0.021	0.127 ±0.021	0.122 ±0.02

Spatial – Temporal Variables	Intervention Group					
	Pre-Intervention Period			Post-Intervention Period		
	B (n=22)	C (n=21)	M (n=22)	B (n=22)	C (n=21)	M (n=22)
Stride Length (m)	1.53 ±0.12	1.62 ±0.12	1.58 ±0.11	1.51 ±0.15	1.61 ±0.16	1.55 ±0.14
Stride Freq. (Hz)	1.01 ±0.072	0.987 ±0.060	0.99 ±0.058	1.01 ±0.055	0.957 ±0.038	0.977 ±0.51
Duty Factor	0.648 ±0.011	0.652 ±0.013	0.651 ±0.012	0.650 ±0.012	0.653 ±0.012	0.649 ±0.011

Table 5.6: Intervention group pre vs. post intervention period spatial and temporal metric comparisons between walking conditions. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod respectively. Post-intervention period percentage change (%) is shown for each spatial-temporal metric. P-values (p) were derived from paired t-tests for each pre vs. post walking condition comparison, respectively. Cohen's d values (d)

were calculated for statistically significant results. Very small, small, medium, large, very large and huge effect sizes are represented by Cohen d values less than 0.01, 0.2, 0.5, 0.8, 1.2 and 2, respectively.

Intervention Group Pre vs. Post Spatial Temporal Metric Comparisons

	B			C			M		
	%	*p*	*d*	%	*p*	*d*	%	*p*	*d*
Speed	-1.71 ±6.85	0.24	-	-3.38 ±8.01	0.073	-	-3.16 ±6.67	**0.042**	0.46
Stride Width	-7.64 ±8.21	**<0.001**	0.87	-4.57 ±10.44	**0.042**	0.47	-6.23 ±9.59	**0.007**	0.63
Stride Length	-1.63 ±4.77	0.14	-	-0.68 ±5.81	0.61	-	-1.98 ±5.01	0.089	-
Stride freq.	-0.12 ±4.08	0.75	-	-2.76 ±4.78	**0.015**	0.58	-1.27 ±2.9	**0.004**	0.46
Duty Factor	0.3 ±1.3	0.32	-	0.13 ±1.87	0.79	-	-0.21 ±1.36	0.45	-

Table 5.7: Control group spatial and temporal variables for the control participants while walking barefoot, conventionally shod, and minimally shod, pre and post intervention period. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod, respectively.

Spatial – Temporal Variables	Control Group					
	Pre-Intervention Period			Post-Intervention Period		
	B (n=22)	C (n=21)	M (n=22)	B (n=22)	C (n=21)	M (n=22)
Speed(m/s)	1.44 ±0.17	1.47 ±0.18	1.44 ±0.17	1.39 ±0.14	1.43 ±0.14	1.43 ±0.14
Stride Width (m)	0.111 ±0.023	0.116 ±0.024	0.117 ±0.027	0.101 ±0.024	0.112 ±0.026	0.11 ±0.023
Stride Length (m)	1.47 ±0.14	1.54 ±0.15	1.51 ±0.14	1.45 ±0.12	1.54 ±0.13	1.51 ±0.12
Stride Freq. (Hz)	0.98 ±0.049	0.95 ±0.052	0.96 ±0.047	0.96 ±0.052	0.93 ±0.043	0.95 ±0.042
Duty Factor	0.649 ±0.013	0.652 ±0.013	0.652 ±0.011	0.653 ±0.010	0.653 ±0.013	0.652 ±0.010

Table 5.8: Control group pre vs. post intervention period spatial and temporal metric comparisons between walking conditions. "B", "C" and "M" represent barefoot, conventionally shod, and minimally shod, respectively. Post-intervention period percentage change (%) is shown for each spatial-temporal metric. P-values (p) were derived from paired t-tests for each pre vs. post walking condition comparison, respectively. Cohen's d values (d) were calculated for spastically significant results. Very small, small, medium, large, very large and huge effect sizes are represented by Cohen d values less than 0.01, 0.2, 0.5, 0.8, 1.2 and 2, respectively.

Control Group Pre vs. Post Spatial Temporal Metric Comparisons									
	B			C			M		
	%	*p*	*d*	%	*p*	*d*	%	*p*	*d*
Speed	-2.86 ±7.18	**0.042**	0.32	-1.98 ±8.74	0.135	-	-0.46 ±7.2	0.54	-
Stride Width	-8.5 ±14.1	**0.016**	0.53	-2.88 ±12.46	0.278	-	-4.29 ±15.82	0.144	-
Stride Length	-0.97 ±5.78	0.309	-	-0.23 ±6.24	0.709	-	0.57 ±5.14	0.739	-
Stride freq.	-1.93 ±3.56	**0.014**	0.54	-1.84 ±4.23	**0.03**	0.47	-1.08 ±3.62	0.14	-
Duty Factor	0.63 ±1.77	0.103	-	0.14 ±1.99	0.776	-	0.01 ±1.33	0.993	-

These results reveal minimally shod walking spatial-temporal variables remain as an intermediate between barefoot and conventionally shod walking spatial-temporal variables, post-intervention period. However minimally shod walking speed did significantly reduce by 3.16% (p = 0.042) after six months of regular footwear use, although the effect size was small (d = 0.46). Stride width reduced for walking conditions after regularly walking in minimal footwear for six months. Stride width reduced by 7.64% ($p < 0.001$), 4.57% ($p = 0.042$) and 6.23% ($p = 0.007$) for barefoot, conventionally shod, and minimally shod walking respectively. Stride frequency significantly reduced for both shod walking conditions during the intervention period. Minimally shod walking stride frequency reduced by 1.26% because its walking speed reduced while its stride length remained comparable, pre versus post intervention period. Conventionally shod walking stride frequency reduced by 2.76% despite either conventionally shod walking stride length or speed to be significantly different. This reveals stride frequency to be a sensitive metric.

The control group's spatial-temporal variables exhibited no changes while walking minimally shod, post-intervention period. Control participants' barefoot walking speed, stride width and stride frequency significantly reduced, post-intervention period. Control participants' stride frequency also reduced while walking conventionally shod.

5.5.2. Lower Limb Joints' Kinematics and Kinetics

Hip and ankle joints motion was quantified in all three anatomical planes. Knee angles were models as a hinge joint so only the joint angle in the sagittal plane is relevant. The angle convention for each joint and in each plane is shown in Table 5.9.

Table 5.9: Joint Kinematics convention table.

Joint Name	Sagittal plane	Coronal Plane	Transverse Plane
Hip	Flexion (+)/ Extension (-)	Adduction (+)/ Abduction (-)	Internal (+)/ External (-) Rotation
Knee	Extension (+)/ Flexion (-)	-	-

Joint Name	Sagittal plane	Coronal Plane	Transverse Plane
Ankle	Dorsiflexion (+)/ Plantarflexion (-)	Inversion (+)/ Eversion (-)	Internal (+)/ External (-) Rotation

Figure 5.5 shows the lower limb joints angles while walking barefoot, minimally shod, and conventionally shod for all participants, pre intervention period. The results show ankle angle is significantly different at heel strike when walking conventionally shod in comparison to the other walking conditions. At heel strike, the ankle is dorsiflexed when walking conventionally shod, 2.76 ± 3.2°, whereas barefoot and minimally shod walking exhibit a statistically significantly more neutral ankle angle of -0.563 ± 2.8° ($p=0.014$) and 0.202 ± 2.78° ($p = 0.006$) respectively. Barefoot and minimally shod ankle angles at heel strike are not significantly different from one another at heel strike. Peak ankle dorsiflexion angle occurs during the transition between terminal stance and pre-swing for all walking conditions. Conventionally shod walking is the most dorsiflexed (12.12 ± 3.65°) and barefoot walking is the least (8.59 ± 2.4°, $p < 0.001$ when compared to both shod conditions), with minimally shod walking an intermediate between the other walking conditions (10.4 ± 3.04°, $p < 0.001$ when compared to both barefoot and conventionally shod conditions).

Peak knee flexion occurs during swing phase for all walking conditions. Peak knee flexion angles are different between all the walking conditions. Peak knee flexion is greatest when walking minimally shod (-67.8 ± 2.92°), least flexed while walking barefoot (-62.06 ± 2.99°, $p < 0.001$ when compared to both shod conditions), with conventionally shod walking peak knee flexion angle an intermediate between the other two conditions (-66.38 ± 3.01°, $p < 0.001$ when compared to both barefoot and minimally shod walking).

Peak hip flexion occurs both at the end of loading response and during swing phase for all walking conditions. Peak hip flexion angles during loading response are not statistically significantly different between walking conditions, however statistically significant differences exist between shod and barefoot walking peak hip flexion angles during swing phase. Both conventionally shod peak hip flexion angle (34.63 ± 5.66°) and minimally shod peak hip flexion angle (33.96 ± 6.66°) are significantly greater than barefoot peak hip flexion angle (32.58 ± 5.36°, $p = 0.004$ and $p = 0.009$ when compared to conventionally and minimally shod walking, respectively), during swing phase.

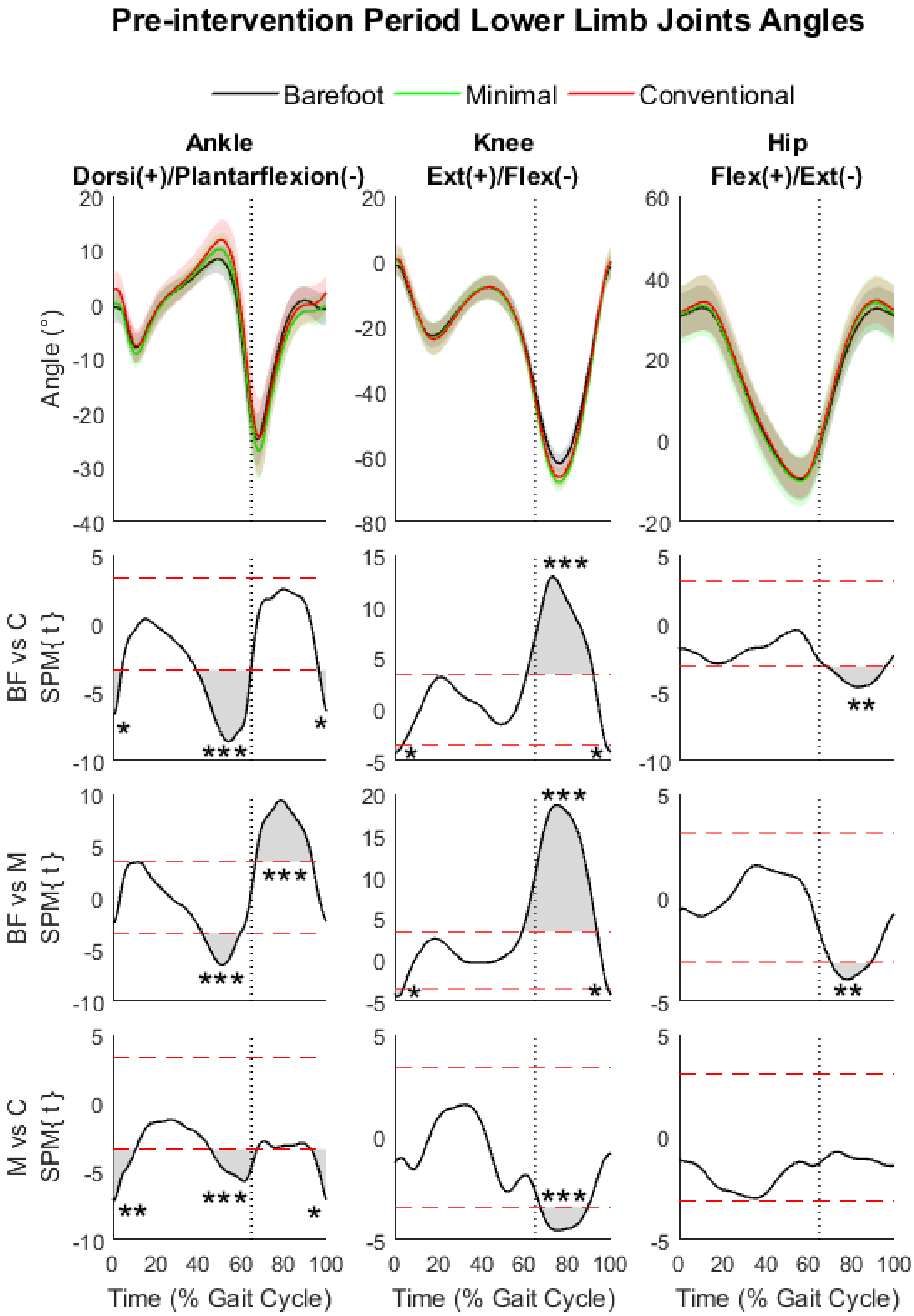

Figure 5.5: Pre-intervention ankle, knee, and hip angles in the sagittal plane (n=50) while walking barefoot (B), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

Figure 5.6 shows the lower limb joint moments while walking barefoot, minimally shod, and conventionally shod for all participants, pre-intervention period. The results show that peak ankle dorsiflexion occurs at the end of terminal stance. The peak ankle plantarflexion moments for barefoot, minimally shod, and conventionally shod are -1.495 ± 0.207Nm/kg, -1.572 ± 0.262Nm/kg and -1.568 ± 0.262Nm/kg, respectively. All walking condition peak plantar flexion moments are not statistically significantly different from one another. However, conventionally shod walking has lower plantarflexion moments throughout mid-stance and the first half of terminal stance, when compared to barefoot ($p < 0.001$) and minimally shod ($p < 0.001$) walking. Barefoot and minimally shod walking ankle moments are both comparable during this section of the stance phase.

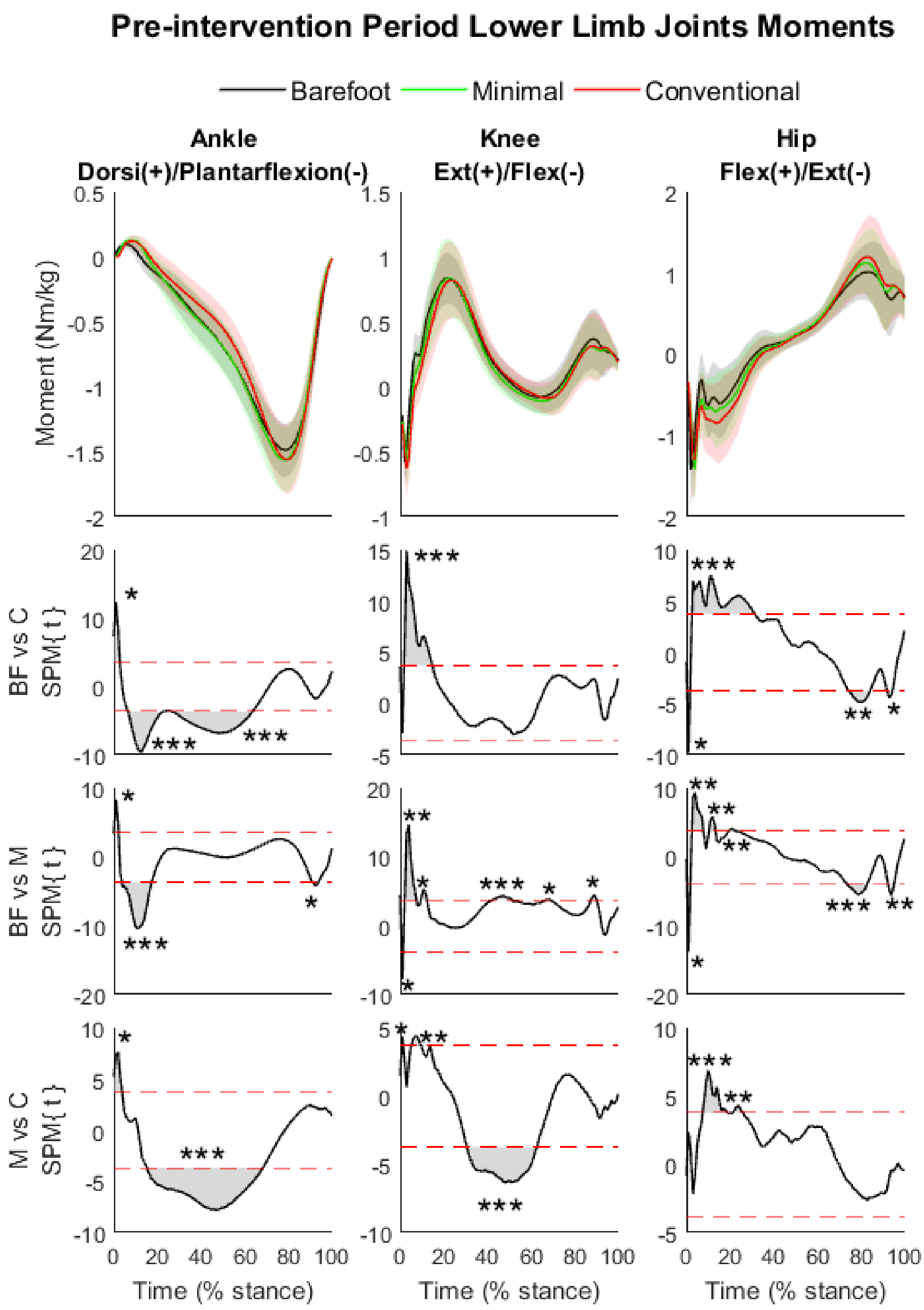

Figure 5.6: Pre-intervention ankle, knee, and hip moments in the sagittal plane (n=40) while walking barefoot (B), minimally shod (M) and conventionally shod (C). One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the stance phase where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

Figure 5.7 shows the lower limb joints' powers while walking barefoot, minimally shod, and conventionally shod for all participants, pre-intervention period. Given that walking is ankle powered it is the most important lower limb joint to review differences in between walking conditions. Ankle power magnitude remains low for the majority of stance phase for all walking conditions and only by the end of the terminal stance does ankle power generation increase substantially. Peak ankle power generation for barefoot, minimally shod, and conventionally shod walking are 4.23 ± 0.814W/kg, 4.587 ± 0.891W/kg and 4.465 ± 1.025W/kg, respectively. All walking condition peak power generation moments are not statistically significantly different from one another. Peak power absorption occurs earlier in terminal stance, immediately before peak power generation. Conventionally shod peak power absorption (-0.873 ± 0.339W/kg) is statistically significantly greater than both barefoot (- 0.7 ± 0.235W/kg, $p < 0.001$) and minimally shod walking (-0.839 ± 0.356, $p < 0.001$) peak power absorption. Interestingly, minimally shod walking is statistically significantly different to barefoot walking during the transition between peak ankle power absorption and generation.

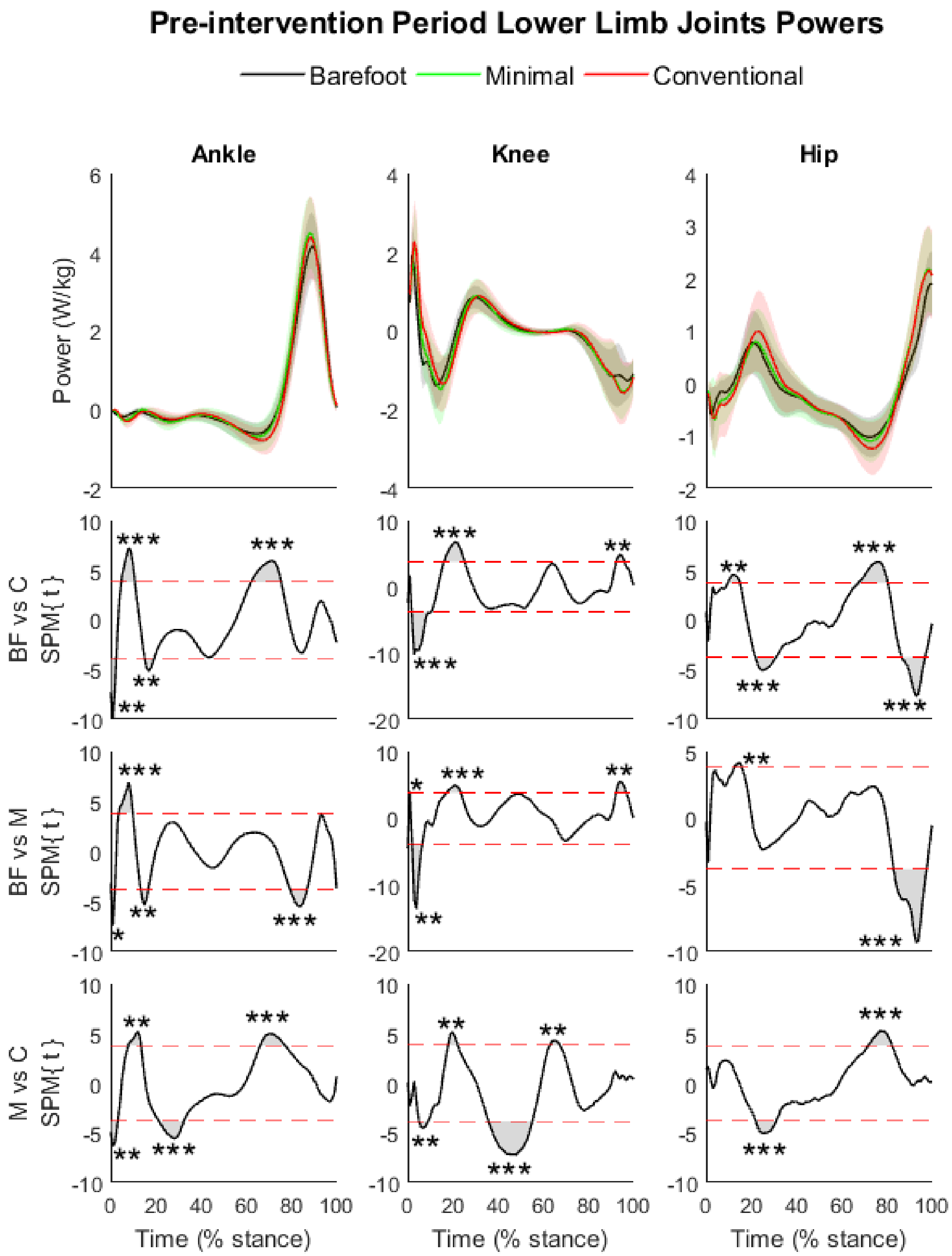

Figure 5.7: Pre-intervention ankle (n=40), knee (n=41) and hip (n=41) powers in the sagittal plane while walking barefoot (B), minimally shod (M) and conventionally shod (C). One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the stance phase where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

Figure 5.8 shows the lower limb joints' angles while walking barefoot, minimally shod, and conventionally shod for the intervention group, pre and post intervention period. The same results for the control group can be seen in Figure 5.9. Peak ankle plantarflexion angles occur at the start of swing phase for all walking conditions for both intervention and control participants, pre and post intervention period. Intervention participant group minimally shod peak ankle plantarflexion angle reduced post-intervention period (-25.76 ± 4.66°, $p = 0.013$) compared to pre-intervention period (-29.99 ± 4.77°). Intervention participant group barefoot and conventionally shod peak ankle plantar plantarflexion angles during walking did not significantly change during pre and post invention period. However, control group minimally shod peak ankle plantarflexion angles also significantly reduced post-intervention period (-26.53 ± 2.77°, $p = 0.03$) compared to pre-intervention period (-25.02 ± 3.07°).

Intervention participant group minimally shod knee flexion angle at initial contact increased post-intervention period (-3.75 ± 4.06°, $p = 0.004$) compared to pre-intervention period (1.98 ± 4.15°). Intervention participant group barefoot knee flexion angle at initial contact also increased post-intervention period (-4.38 ± 3.2°, $p = 0.024$) compared to pre-intervention period (0.16 ± 3.72°). Control group knee angles at initial contact did not significantly change pre versus post intervention period for any walking condition.

Intervention participant group minimally shod hip flexion angle at initial contact increased post-intervention period (34.87 ± 4.87°, $p = 0.049$) compared to pre-intervention period (30.4 ± 7.26°). Intervention participant group barefoot and conventionally shod hip angles at initial contact angles during walking did not significantly change during pre and post invention period. Additionally, control group hip angles at initial contact did not significantly change pre versus post intervention period for any walking condition.

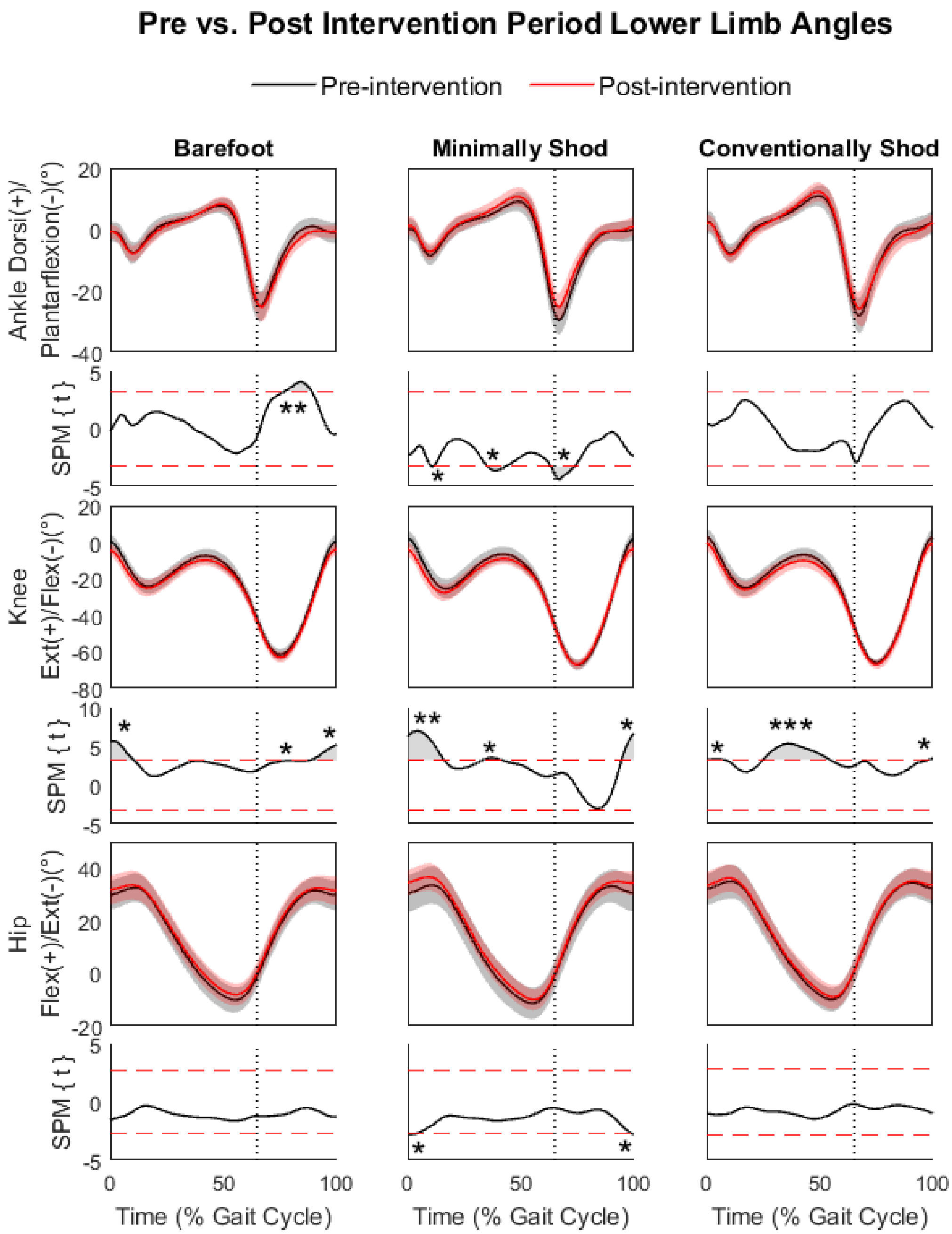

Figure 5.8: Intervention group pre and post intervention period ankle, knee and hip angles in the sagittal plane while walking barefoot (B; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

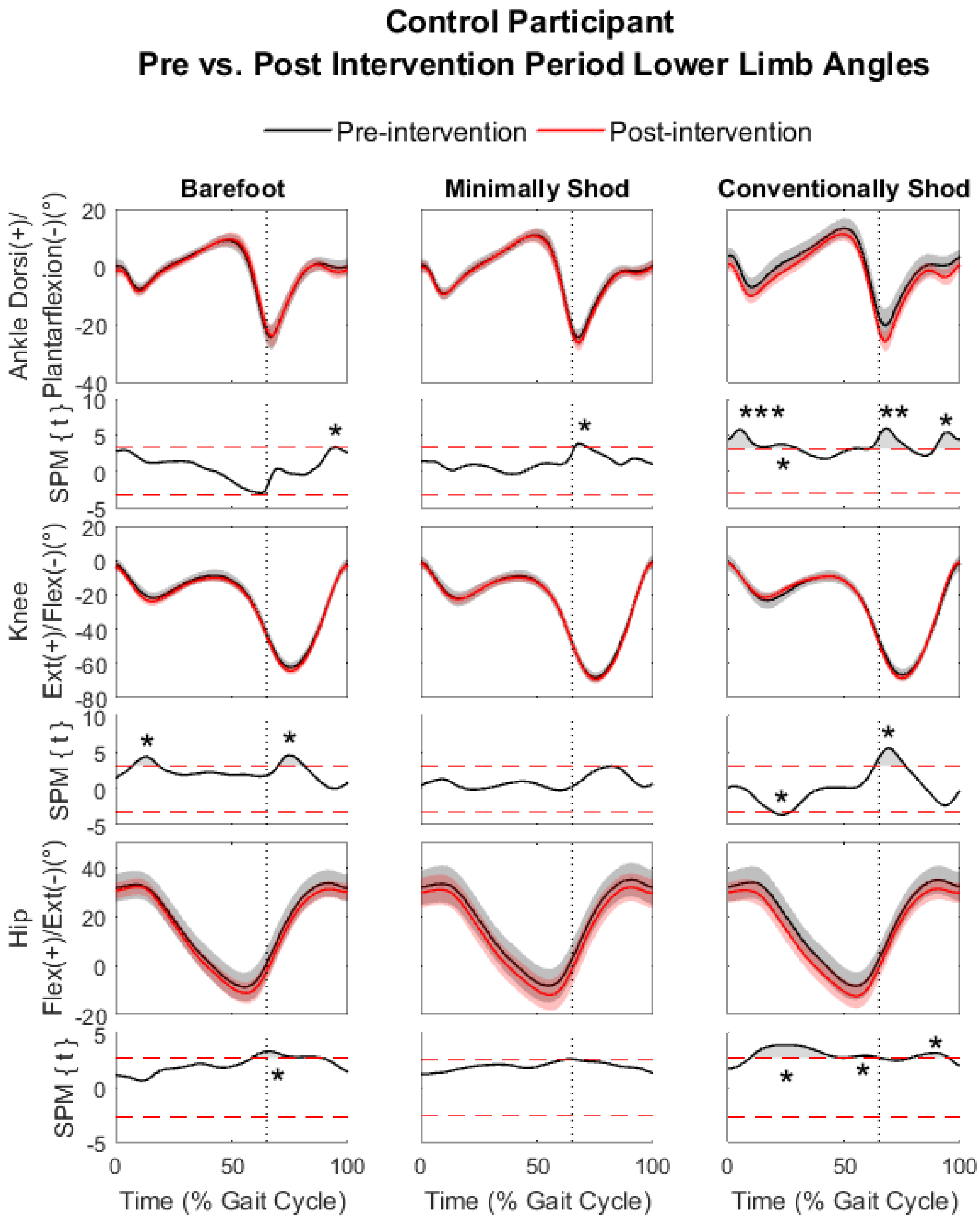

Figure 5.9: Control group pre and post intervention period ankle, knee and hip angles in the sagittal plane while walking barefoot (B; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001, respectively.*

5.5.3. Foot Kinematics

Table 5.10 shows the averages and standard deviations of the ROMs of foot width (both absolute and normalised), the longitudinal arch, and the transverse arch, while walking barefoot for both the control and intervention groups, pre and post intervention period. Statistically significant differences between the pre and post intervention period tests were detected with paired t-tests (Table 5.11). The intervention group exhibited no changes to the measured dynamic foot variables, post-intervention period. The control group foot width ROM increased (in both absolute and normalised measures), and longitudinal arch ROM decreased.

Table 5.10: Dynamic foot widths, relative foot widths, longitudinal arch angles and transverse arch angles derived from the Ghent foot model. All the key variables are expressed as their range of motion (ROM). Normalised foot width is a dimensionless metric where foot width was normalised to height.

Foot Model Variables	Intervention Group		Control Group	
	Pre (n=22)	Post (n=22)	Pre (n=24)	Post (n=24)
Foot Width ROM (mm)	10.52 ±1.54	11.24 ±1.84	9.90 ±2.06	10.96 ±1.93
Norm. Foot Width ROM	6.12 ±1.00	6.51 ± 1.03	5.77 ±1.23	6.38 ±1.16
Longitudinal arch ROM (°)	7.32 ±2.26	7.77 ± 2.34	8.43 ±2.86	7.49 ±2.12
Transverse arch ROM (°)	4.48 ±0.98	4.5 ± 1.40	4.60 ±1.67	5.07 ±1.23

Table 5.11: Intervention and control groups' pre vs. post intervention dynamic foot metric comparisons. Post-intervention period percentage change (%) is shown for each foot metric. P-values (p) were derived from paired t-tests for each pre vs. post walking condition comparison, respectively. Cohen's d values (d) were calculated for statistically significant results. Very small, small, medium, large, very large and huge effect sizes are represented by Cohen d values less than 0.01, 0.2, 0.5, 0.8, 1.2 and 2 respectively.

Foot Kinematic Variables	Pre vs. Post Intervention Period Foot Kinematics					
	Intervention Group			Control Group		
	%	*p*	d	%	*p*	d
Foot Width ROM	7.64 ± 15.69	0.051	-	12.19 ± 13.98	**<0.001**	0.834
Norm. Foot Width ROM	7.64 ± 15.69	0.26	-	12.19 ± 13.98	**<0.001**	0.841
Longitudinal Arch ROM	11 ± 34.71	0.061	-	-7.59 ± 23.22	**0.041**	0.44
Transverse Arch ROM	7.47 ± 48.9	0.95	-	26.01 ± 61.35	0.29	-

5.6. Discussion

5.6.1. Spatial Temporal Variables

This section of the discussion addresses one of the central research questions within this chapter: What differences exist between barefoot, minimally shod, and conventionally shod walking on spatial-temporal variables and how do these variables change after six months of minimal footwear use for each walking condition?

The first spatial temporal variable hypothesis (1.1) of the study was that walking speed will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate. This hypothesis was rejected.

Average walking speed was greatest while conventionally shod, lowest while barefoot and minimally shod walking was in-between the other two walking conditions, however none of the walking conditions walking speeds were significantly different from one another. This agrees with some studies that reviewed the walking velocities of similar walking conditions (Oeffinger et al., 1999, Wolf et al., 2008). However other studies found barefoot walking to be significantly slower than conventionally shod walking (Lythgo et al., 2009, Wirth et al., 2011, Moreno-Hernández et al., 2010). The studies that found no differences in walking velocity had much smaller participant groups. This suggests that barefoot walking is significantly slower than conventionally shod walking, it just requires a large enough group to find it.

The second spatial temporal variable hypothesis (1.2) of the study was that six months of minimal footwear use will result in a reduction of walking speed while walking minimally shod. This was proven to be true as minimally shod walking speed significantly reduced post intervention period. The experience gained in minimally shod walking by the intervention participants, developed spatial-temporal variables closer to those of barefoot walking. Minimally shod walking speed reduced by 3.16% (becoming slower than barefoot walking speed, pre and post intervention period). However minimally shod walking remained an intermediate between barefoot and conventionally shod walking for many spatial-temporal variables. This suggests that minimally shod walking experience will influence gait but only to a limited extent. It should also be noted that control group barefoot walking speed reduced by 2.86% post intervention period. This could be because control participants were restricted to the footwear they wore most regularly before the study started for 70% of the time throughout the intervention period. This unintentional intervention on the control group may have caused the observed influence above.

The third spatial temporal variable hypothesis (1.3) of the study was that stride length will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate. This was proven to be partially true.

Conventionally shod walking stride length was 4.53% greater than barefoot walking and average minimally shod walking stride length was in-between the two other walking conditions but was not significantly different from either. Wirth and colleagues found both minimally shod walking stride length and cadence to be a significant intermediate between barefoot and conventionally shod walking (Wirth et al., 2011). However, the minimal footwear incorporated in that study was different from the ones used in the present study. The spatial and mechanical properties of the Wirth minimal footwear are not reported, so it is possible the differences between the minimal footwear influenced the differences in our results. Barefoot and conventionally shod walking stride length comparisons agree to the findings within the present study, with other studies that reviewed the stride length of different walking conditions of healthy young adults (Lythgo et al., 2009, Keenan et al., 2011, Wirth et al., 2011, Majumdar et al., 2006), and children (Oeffinger et al., 1999, Moreno-Hernández et al., 2010, Wolf et al., 2008, Lythgo et al., 2009). However, the results of the present study revealed that stride length is directly dependent on walking velocity, therefore the lower barefoot walking stride length was ultimately caused by the relatively slower barefoot walking speed compared to conventionally shod walking. Interestingly our study found no significant differences between the walking velocities of the walking conditions.

The fourth spatial temporal variable hypothesis (1.4) of the study was that six months of minimal footwear use will result in a reduction of stride length while walking minimally shod. This hypothesis was rejected, as minimally shod walking post intervention period did not significantly reduce even though average minimally shod walking stride length was lower post intervention period. Control group stride length also did not significantly change post intervention period for all walking conditions. Interestingly, intervention group stride width reduced in all walking conditions for the post-intervention period. This suggests that regular use of minimal footwear improves medio-lateral stability and spatial confidence while walking. It has been found that medial-lateral stability while walking is increased as a result of wearing minimal footwear when compared to conventional shod walking (Cudejko et al., 2020). It should also be noted that control group stride width also reduced while walking barefoot post intervention period. This may be linked to the control groups reduction in walking speed while barefoot post intervention period. There is a notable trend that walking is positively correlated to stride width.

Overall, the spatial-temporal results show a non-significant trend for minimally shod walking to be an intermediate between barefoot and conventionally shod walking in the pre intervention period. However, the only statistically significant difference is between conventionally shod and barefoot walking stride length. Post-invention period small changes in some minimally shod spatial temporal variables tend towards those of barefoot walking. This suggests that six months of regular minimally shod walking influences minimally shod walking gait.

5.6.2. Kinematics and Kinetics of the Lower Limb Joints

General kinematics and kinetics trends were comparable to a previous validation study (Kadaba et al., 1989). The kinematics and kinetics of the knee and ankle within this study are highly comparable to the work of previous studies while walking in similar walking conditions (Zhang et al., 2013, Oeffinger et al., 1999, Morio et al., 2009). This section of the discussion addresses one of the central research questions within this chapter: What differences exist between barefoot, minimally shod, and conventionally shod walking kinematics and kinetics of the lower limb joints and how do the kinematics and kinetics change after six months of minimal footwear use for each walking condition?

The first lower limb joint kinematic and kinetic hypothesis (2.1) of the study was that conventionally shod walking will produce a greater ankle dorsiflexion angle at initial contact than both barefoot and minimally shod walking. This was proven to be true. Barefoot walking has an average plantarflexion angle of $0.563 \pm 2.8°$ at heel strike, whereas conventionally shod walking has an average dorsiflexion angle of $2.76 \pm 3.2°$. This agrees with studies that have investigated the kinematics of barefoot and conventionally shod walking (Oeffinger et al., 1999, Morio et al., 2009, Zhang et al., 2013). Minimally shod walking was also significantly more plantarflexed than conventionally shod walking at initial contact, with an average dorsiflexion angle of $0.202 \pm 2.78°$. This indicates heel strike is kinematically the most pronounced while walking conventionally shod. Heel strike is likely to be more pronounced while conventionally shod because additional cushioning has been shown to cause increased dorsiflexion at initial contact (Lieberman et al., 2010). The greater dorsiflexion angle exhibited while walking conventionally shod is unlikely to have a large influence during loading response given the plantar pressure results within the fourth chapter of this thesis. These results show that the heel region of conventionally shod peak plantar pressure distributions were not significantly different to those of the other walking conditions. In fact, there were no significant peak plantar pressure distribution differences between both all the walking conditions pre-intervention period and within walking conditions pre versus post intervention period. This means that all the kinematic and kinetic differences observed within the present chapter were not great enough to influence plantar pressure distributions.

The second lower limb joint kinematic and kinetic hypothesis (2.2) of the study was that the majority of shod walking peak ankle, knee and hip angles will be greater than barefoot walking. This was proven to be true. Both minimally and conventionally shod walking produced greater peak lower limb joint angles than barefoot walking during numerous points in the gait cycle. Conventionally and minimally shod walking produced average peak ankle dorsiflexion angles during terminal phase of $12.12 \pm 3.65°$ and $10.4 \pm 3.04°$, respectively, whereas barefoot walking produced an average peak ankle dorsiflexion angle during terminal phase of $8.59 \pm 2.4°$. This agrees with findings from previous literature (Zhang et al., 2013, Kung et al., 2015). Conventionally and minimally shod walking also produced average peak knee flexion during swing phase of $66.38 \pm 3.01°$ and $67.8 \pm 2.92°$, respectively, whereas barefoot walking produced an average peak knee flexion angle during swing phase of $62.06 \pm 2.99°$. In addition to this, conventionally and minimally shod walking produced average peak hip flexion during swing phase of $34.63 \pm 5.66°$ and $33.96 \pm 6.66°$, respectively, whereas barefoot walking produced an average peak hip flexion angle during swing phase of $32.58 \pm 5.36°$. Most peak lower limb joint angles in the sagittal plane are greater while walking in both shod conditions than barefoot walking because stride length whilst walking in both shod conditions are greater than barefoot walking stride length. This means that the lower limb joints need to cover a greater range of motion, therefore at least some of the peak lower limb joint angles throughout the gait cycle will have to be greater during some point in the gait cycle.

The third lower limb joint kinematic and kinetic hypothesis (2.3) of the study was that peak ankle plantarflexion moment will be greatest while walking conventionally shod and lowest while barefoot. This hypothesis was rejected as conventionally shod walking produced peak ankle plantar flexion angles that were not statistically significantly greater than those of barefoot walking. This is in contrast to findings from Oeffinger et al. (1999), however, the majority of the literature agrees that there are no significant differences in peak ankle flexion moments while walking barefoot and conventionally shod (Zhang et al., 2013, Keenan et al., 2011, Dames and Smith, 2016). Even though peak ankle moments between barefoot and conventionally shod walking revealed no significant differences, an interesting finding observed within the present study was that barefoot and minimally shod walking ankle plantarflexion moments are both greater than conventionally shod walking during the majority of stance phase. The extrinsic and intrinsic foot muscles during barefoot and minimally shod walking must be working harder at this point within the stance phase. This offers a potential explanation as to why six months of regular minimal footwear use led to increased foot strength. A finding that was observed in third chapter of the present thesis.

The fourth lower limb joint kinematic and kinetic hypothesis (2.4) for the study was ankle power will be lowest while walking barefoot, and greatest while walking conventionally shod. This was mainly rejected. The peak ankle power generations at pre-swing were found to be comparable for all walking conditions pre-intervention period. However, conventionally shod walking ankle power absorption during terminal stance was greater than the other walking conditions. This agrees with findings from Oeffinger et al. (1999). This indicates that more negative work is taken by the ankle while walking conventionally shod. Walking is predominantly ankle powered, with the greatest power occurring during pre-swing (Winter, 1991). This means that the finding within the present study indicate that conventionally shod walking takes the most work for each stance phase, thereby making it the least efficient out of all the walking conditions. However conventionally shod walking does have the greatest stride length so it could be argued that the cost of locomotion will be comparable for all the walking conditions.

The fifth lower limb joint kinematic and kinetic hypothesis (2.5) of the study was that six months of regular minimal footwear use will lead to minimally shod walking peak lower limb joint angles trending towards those of barefoot walking. This was proven to be true. Intervention group minimally shod walking peak ankle plantarflexion angle, and knee and hip angles at initial contact tended towards those of barefoot walking post intervention period. In addition to this, no other changes in minimally shod walking lower limb joint angles tended away from barefoot walking.

Initially, intervention group minimally shod ankle angle during swing phase was more plantarflexed than barefoot walking, pre-intervention period. In addition to this, the knee is most flexed during swing phase when walking minimally shod. It is likely these results are caused by the lack of familiarity for the footwear from the participant. Minimal footwear has a large toe box area and a general looser feel when worn, which many conventionally western shod societies feel unaccustomed to. In addition to this, conventional footwear has been shown to reduce foot position awareness (Robbins et al., 1995). This results in overcompensating ankle plantarflexion and knee flexion to match the participant's perception required for toe clearance. Once experience has been gained in minimally shod walking, after the six months of regular minimal footwear use, intervention participants no longer plantarflex as severely during the swing phase. This suggests the intervention group developed kinesthesia for minimally shod walking after using the minimal footwear regally for six months**.** Franklin and colleagues hypothesised that minimal footwear improves the stimulation of the plantar mechanoreceptors in comparison to conventional footwear (Franklin et al., 2015). Holowka et al. found habitually barefoot walkers with thick foot calluses lost no plantar mechanoreceptor sensitivity when compared to barefoot walkers with thin or no foot callouses whereas conventionally shod walkers lost sensory feedback (Holowka et al., 2019). This research combined the findings of the present study suggests that minimal footwear allows for greater plantar mechanoreceptor sensory feedback than conventional footwear while still protecting the foot.

Intervention group knee flexion increased during loading response while walking minimally shod during the post-intervention period, making its kinematic properties closer to barefoot walking. It appears that minimally shod walking experience has conditioned the participants to absorb impact with a more flexed knee. The participants are absorbing the additional impact forces through knee flexion now that they have overcome their perception of cushioning level associated to the minimal footwear. The lack of cushioning is now countered by knee flexion to maintain the body's desired leg stiffness (McMahon et al., 1987, Ferris and Farley, 1997, Farley et al., 1998).

Another point of interest is how the hip joint is linked to the knee joint during gait. In the instances when the minimally shod walking conditions have more flexed knees when compared to the barefoot walking condition, the hip also tends to be more flexed. This shows how the two joints work as pairs for much of the gait cycle when walking. The differences in hip angles between the walking conditions are less than the differences observed between the three walking conditions ankle and knee angles. This suggests that different walking conditions influence on the joint start to diminish further by the hip joint. With these results we cannot answer how far up the body footwear has influence on but we hypothesis differences between shod and unshod walking would be negligible after the hip joint.

Control group minimally shod walking peak ankle plantarflexion angle significantly increased post-intervention period. This is unlikely to be a systematic error given that this is the opposite result shown by the intervention group. We expected no differences in the control group and are unsure as to why this is the case. The only potential explanation that caused this is that the control participants had some recollection of wearing the minimal footwear during the pre-intervention period tests and walked with more confidence in the footwear without having gained experience in the footwear thereby causing this increase in ankle plantarflexion during swing phase. Control participant conventionally shod walking ankle angles were more plantarflexed for most of the gait cycle post intervention period. As the intervention participants do not show the same response, we do not believe this to be a systematic error. One possibility is the fact that control participants were instructed to wear their conventional footwear as their "regular" footwear. In practice many control participants wore out their "regular" shoes before the end of the study and replaced the footwear with shoes that often were completely different with regards to their mechanical properties. Intervention participants had been wearing the prescribed minimal footwear for the entirety of the intervention period so still had the same conventional footwear to be tested in for the post-intervention tests in more or less the same condition as they were for the pre-intervention tests.

5.6.3. Foot Kinematics

This section of the discussion addresses one of the central research questions within this chapter: What is the influence of six months of minimal footwear use on foot compliance while walking barefoot?

The first foot kinematic hypothesis of the study was that six months of regular minimal footwear use will increase dynamic foot spread about the ball of the foot while walking barefoot. This hypothesis was rejected as no changes in foot width ROM were found in the intervention group. Dynamic foot width spread about the ball of the foot was calculated as 10.6% for the intervention group and 10.4% for the control group. This finding was slightly higher than the 7.8% change in dynamic foot width spread found in children by Wolf et al. (2008). Wolf and colleagues also found dynamic foot spread was significantly lower in children while conventionally shod at 2% (Wolf et al., 2008), and although not investigated in this study, it is likely that conventional footwear would continue to limit dynamic foot spread in healthy adults, whereas minimal footwear would not. It has been shown people typically wear footwear that is too narrow (Frey et al., 1993) which would therefore restrict dynamic foot width spread. Further research should be conducted to investigate how different types of footwear influence dynamic foot spread.

The second foot kinematic hypothesis of the study was that six months of regular minimal footwear use will increase arch stiffness while walking barefoot. This hypothesis was rejected as no changes in longitudinal arch ROM were found in the intervention group. The medial longitudinal arch is a key feature of the windlass mechanism that is vital for efficient bipedal gait (Hicks, 1954, Griffin et al., 2015). The results within the present study show a medial longitudinal arch ROM of 7.32° and 8.43° for intervention and control participants' pre intervention period, respectively. In contrast Kelly and colleagues found a medial longitudinal arch ROM of roughly 14° (Kelly et al., 2015). This is likely because and walking velocity was controlled to 1.25m/s within the Kelly et al. (2015) which is lower than the average barefoot walking speed of 1.49m/s within the present study, and Pataky et al. (2008) have shown higher walking speeds caused reduced medial longitudinal arch ROM. In addition to this, the Kelly et al. (2015) study used an established 3D foot model created using inverse dynamics (Leardini et al., 2007) to calculate longitudinal arch angle in the sagittal plane whereas the present study simply used three markers on the foot and calculated the angle between 3 points in the 3D space. Further comparisons between the longitudinal arch ROM in the present study and the literature is limited as the majority of foot kinematics are based on 3D foot models (Carson et al., 2001, De Mits et al., 2012, Kidder et al., 1996, Leardini et al., 1999, Leardini et al., 2007).

The dynamic foot metric results derived from the Ghent foot model rejected all hypothesis relating to the foot kinematics. Intervention participants exhibited no changes, whereas the control participants exhibited many of the changes we hypothesised for the intervention participants. Firstly, control group foot width ROM increased, post-intervention period. However, the results show that control group foot width ROM is much lower than the intervention group, pre-intervention period. Furthermore, intervention group foot width ROM is greater than the control group, post-intervention period. Although hard to quantify from the future footwear questionnaire, we hypothesize that control participants typically wore more restrictive footwear more frequently prior to the start of the study. As control participants were confined to wearing the shoes they most regularly wore, the use of their more restrictive footwear dropped, leading to a more flexible forefoot. Restricting the control groups' footwear use, is in hindsight, is a limitation to the study. Secondly control group longitudinal arch ROM reduced post-intervention period, indicating a stiffer foot. However, control group longitudinal arch ROM was considerably greater than the intervention group, pre-intervention period. Once control group longitudinal arch height reduced post intervention period, it was comparable to the intervention group, pre or post intervention period. This further supports the idea that the restriction of footwear use for control participants during the intervention period had some influence.

Both control and intervention group foot kinematics reviewed in this study converge to be comparable by the post intervention period. This suggests that the influence of footwear on foot spread ROM, longitudinal arch ROM and transverse arch ROM are limited for healthy adults. Studies have shown plantar pressure distribution differences between habitually barefoot and conventionally shod communities during walking (D'Août et al., 2009) and growing up barefoot causes noticeable differences in foot morphology versus growing up conventionally shod (Hollander et al., 2017a), indicating that footwear use has its greatest influence on foot morphology during childhood. Whether this is also true for the foot kinematics is debatable as to the best of our knowledge no study has shown the foot kinematics for habitually barefoot communities. From our results it appears that six months of regular minimal footwear use has no influence on foot kinematics but reducing use of the most constricting footwear types does have a positive benefit on foot kinematics. However, this is mainly speculation and further research is required.

The transverse arch has been shown to be an important feature of foot morphology for foot stiffness (Venkadesan et al., 2020). Our results show that six months of regularly walking in minimal footwear has no influence on the transverse arch ROM. To the best of our knowledge no one else has looked at the ROM of the transverse arch in the mid foot, all the current literate has focused on the transverse arch flexibility in the forefoot (Kondo et al., 2017, Kudo et al., 2014).

5.6.4. Limitations

The study had a number of limitations. This study placed markers onto the outside of the footwear as opposed to cutting holes in the conventional and minimal footwear in order to attach the markers directly to the foot. This means there will always be some discrepancy between the recorded versus actual kinematics and kinetics relating to the foot markers whilst walking shod as the movement of the markers on the external surface of the shoe are partly measuring the deformation of the shoe rather than foot kinematics (Reinschmidt et al. 1992). Another limitation is that the Ghent foot model employed in this study has not been validated for inter-examiner use and the authors of the model report they are unsure on the effect the weight distribution inequality during stance phase (De Mits et al., 2012). This limitation reduces the credibility of the foot kinematics. Another limitation is that 1D-SPM is a highly sensitive tool which would often reveal statistically significant results for biological irrelevant results for the kinematic and kinetics analysis. These types of results often occurred as a result of the boundary effect, where the sensitivity of a one-dimensional statistical analysis is drastically higher at the start and end of the one-dimensional data. Statistically significant but biologically irrelevant differences between walking condition kinematics and kinetics can also be caused by either the magnitude or time period of differences between walking conditions to be so small that it is clear those differences would have no influence on gait characteristics. This meant care had to be taken when interpreting the results that used 1D-SPM and is why the discussion is mainly limited to hypothesis driven discussion.

5.7. Conclusion

The gait characteristics while walking barefoot, minimally shod, and conventionally shod follow similar trends however differences exist between all the walking conditions. Minimally shod walking exhibits spatial-temporal variables, kinematics and kinetics that are an intermediate, in-between barefoot and conventionally shod walking. Six months of regular minimally shod walking causes walking speed, stride width, stride frequency, and kinematics and kinetics of the ankle, knee and hip to tend towards those of barefoot walking while walking minimally shod, however minimally shod walking still remains a unique and intermediate walking condition between barefoot and conventionally shod walking.

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6. Chapter 6: Discussion and Conclusion

1.1. Discussion

This thesis comprehensively describes the influence of minimal footwear on the biomechanics of walking with regards to gait characteristics and foot function. To do so, the research presented in this thesis aimed to answer the central research questions stated in the introduction. These questions are reiterated below:

1. What biomechanical differences exist between barefoot, minimally shod and conventionally shod walking in healthy adults?
2. Can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function?
3. What are the long-term effects of walking in minimal footwear?

In order to answer these questions three separate studies were conducted; the minimal footwear adaption (MFA), the experienced minimally shod (EMS), and the indigenous footwear studies. The MFA study was the largest of the studies and answered the first two research questions – what differences exist between barefoot, minimally shod, and conventionally shod walking in healthy adults and can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function? The MFA study was a prospective cohort study where healthy conventionally western shod participants were required to wear minimal footwear for a six-month intervention period. Gait characteristics while walking barefoot, minimally shod, and conventionally shod (the walking conditions), as well as foot function were tested in pre and post intervention period tests. The MFA study measured and evaluated:

- Biometrics (height, mass, leg length, foot length and width, toe length, nav. height).
- Participant activity and footwear habits throughout the intervention period.
- Footwear properties (mass, spatial metrics, and mechanical metrics).
- Participant health and footwear wearing habit history.

- Spatial and temporal plantar pressure patterns.
- Foot strength
- Kinematics and kinetics (Spatial-temporal variables, lower limb joint kinematics and kinetics, and foot kinematics).

Both the EMS and indigenous minimal footwear study answered the third research question – what are the long-term effects of walking in minimal footwear? Both studies also contributed additional information towards the first research question – what differences exist between barefoot, minimally shod, and conventionally shod walking in healthy adults?

The EMS study used habitually conventionally western shod participants that had transitioned to predominant minimal footwear use a minimum of six months prior to testing (2.5 ± 2.4 yrs minimal footwear experience) to investigate gait characteristics while walking barefoot and minimally shod, as well as foot function. The EMS study measured and evaluated:

- Biometrics (height, mass, leg length, foot length and width, toe length, nav. height).
- Footwear properties (mass and spatial metrics).
- Participant health and footwear wearing habit history.
- Spatial and temporal plantar pressure patterns.
- Foot strength

The indigenous footwear study investigated gait characteristics and foot function of three indigenously minimally shod communities and one habitually conventionally western shod community. The indigenously minimally shod communities were Kolhapuri Indians from a rural village of Athani in the state of Karnataka, Sami Scandinavians from around Inari, Northern Finland, and a Ju|’hoan San heritage at the Nyae-Nyae Concession Area, Otjizondjupa region, Namibia. The habitually conventionally western shod community were Europeans living in Belgium. The four groups had barefoot and minimally shod walking gait characteristics evaluated. The indigenously minimally shod groups used their indigenous minimal footwear for the minimally shod walking condition and the habitually conventionally western shod group used commercial minimal footwear. The habitually conventionally western shod group also had gait characteristics evaluated while walking in their conventional footwear. The indigenous minimal footwear study measured and evaluated:

- Biometrics (height and mass).
- Footwear properties (mass).
- Spatial plantar pressure patterns.
- Temporal plantar pressure patterns (only in the habitually conventionally western shod group).
- Foot strength (only in the San group).

These studies, combined, successfully answered the research questions, and addressed the aims and objectives stated in the thesis introduction. Table 6.1 addresses the outcome of each hypothesis.

Table 6.1: Complete thesis hypotheses and outcomes. Inconclusive hypothesis outcomes are the result of the limitations associated with the HBM group. The hypotheses are also colour coded to indicate which chapter they belong to. Chapter 2 = blue, chapter 3 = green, chapter 4 = orange and chapter 5 = red.

Hypotheses	Accepted /Rejected
Minimally shod walking peak plantar pressure will be less than barefoot walking and greater than conventionally shod walking for habitually conventionally western shod adults.	Rejected
Inexperienced minimally shod walkers will heel strike most distally when walking barefoot and least while walking conventionally shod, with minimally shod walking as an intermediate for habitually conventionally western shod adults.	Accepted

Walking speed will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate for habitually conventionally western shod adults.	Rejected
Stride length will be greatest when conventionally shod and lowest while barefoot, with minimally shod walking being an intermediate, for habitually conventionally western shod adults.	Rejected
Conventionally shod walking will produce a greater ankle dorsiflexion angle at initial contact than both barefoot and minimally shod walking.	Accepted
Shod walking peak ankle, knee and hip angles will be greater than barefoot walking.	Accepted
Peak ankle plantarflexion moment will be greatest while walking conventionally shod and lowest while barefoot.	Rejected
Peak power will be lowest while walking barefoot, and greatest while walking conventionally shod.	Rejected
Six months of regular minimal footwear use will produce minimally shod walking peak plantar pressure distributions statistically indistinguishable from their barefoot plantar pressure distributions.	Accepted
Six months of regular minimal footwear use will lead to minimally shod walking heel-to-toe plantar pressure progression throughout stance phase being closer to that of barefoot walking.	Rejected
Six months of regular minimal footwear use will result in a reduction of walking speed while walking minimally shod, for habitually conventionally western shod adults.	Accepted

Six months of regular minimal footwear use will result in a reduction of stride length while walking minimally shod, for habitually conventionally western shod adults.	Accepted
Six months of regular minimal footwear use will lead to minimally shod walking peak ankle, knee, and hip angles tending towards those of barefoot walking.	Accepted
Six months of regular minimal footwear use will increase dynamic foot spread about the ball of the foot while walking barefoot, for habitually conventionally western shod adults.	Rejected
Six months of regular minimal footwear use will increase arch stiffness while walking barefoot, for habitually conventionally western shod adults.	Rejected
Six months of regular minimal footwear use increases foot width, for habitually conventionally western shod adults.	Rejected
Foot strength increases in conventionally western shod populations after using minimal footwear for daily activity after a six-month period.	Accepted
Foot strength continues to increase in conventionally western shod populations if regular use of minimal footwear is maintained after a six-month period.	Rejected
Normalised peak plantar pressure distributions in any shod condition will be equivalent to the barefoot walking condition for habitually minimally shod communities.	Accepted

Conventionally western shod adults will have comparable foot strengths to habitually barefoot and/or minimally shod adults given sufficient minimally shod walking experience.	Inconclusive
Experienced minimally shod walkers will have greater foot width than inexperienced minimally shod walkers.	Rejected

General answers to the central research questions can be derived from inspection of the outcomes of the hypotheses in Table 6.1, and each outcome is discussed thoroughly within this thesis. The first research question was what differences exist between barefoot, minimally shod, and conventionally shod walking in healthy adults? The gait characteristics were defined via an array of different results all with varying outcomes as a result generalisation must be done with caution, however, overall, the gait characteristics results of this research could be interpreted such that barefoot walking was the most refined whereas conventionally shod walking was the most robust. This research also found that overall, minimally shod walking gait characteristics to be an intermediate between barefoot and conventionally shod walking. Most of these differences were highlighted by the kinematics and kinetics results. However, the centre of pressure results highlighted differences between the walking conditions, where the plantar pressure distributions could not. This suggests that footwear influences temporal plantar pressure patterns more than spatial plantar pressure characteristics.

The second research question was can transitioning from regular conventionally shod walking to regular minimally shod walking influence healthy adult gait characteristics and foot function? This research found six months of regular minimal footwear use has a limited influence on minimally shod walking gait characteristics that, overall, tend towards barefoot walking gait characteristics. This influence is slight and minimally shod walking remains distinctly different from both barefoot and conventionally shod walking. These differences were found on inspection of some of the kinematic results, both minimally shod walking spatial and temporal plantar pressure patterns showed no significant changes after six months of regular minimal footwear use. This means that six months of regular minimal footwear use does not sufficiently alter minimally shod walking gait characteristics enough to significantly influence the plantar pressures produced during walking.

Transitioning from regular conventionally shod walking to regular minimally shod walking was also shown to influence foot strength. Six months of regular minimal footwear use increased foot strength by 57.4%. This increase in foot strength is likely to have occurred as a result of greater ankle plantarflexion moments throughout the majority of stance phase while walking minimally shod when compared to conventionally shod walking (results shown in chapter 5 and Appendix E). The tibialis anterior, soleus, gastrocnemius medialis and lateralis, peroneus longus and peroneus brevis and extensor digitorum longus are directly responsible for the plantarflexion moment produced (Hunt et al., 2001), however it is likely that increased plantarflexion ankle moments will increase intrinsic foot muscles activation in order to aid longitudinal arch function when the longitudinal arch is experiencing greater loading (Kirby, 2017). The intrinsic muscles that are likely to increase in activation in this instance are the Abductor Hallucis, Flexor Digitorum Brevis and Quadratus Plantae, as Kelly et al. (2014) found that they are responsible in supporting the longitudinal arch. Increased activation of these muscles will lead to hypotrophy. Some of these muscles will likely contribute to the value of TFS (toe flexion strength) measured in the foot strength test employed in this research. Unfortunately, it isn't possible to definitively specify if these muscles contributed to the TFS foot strength metric in this research or the relative plantar flexor muscle activations between walking conditions. Future studies investigating the long-term influence of minimal footwear during walking should pair foot strength evaluation via dynamometry with MRI scans of the foot, much like Ridge et al. (2019). Future studies should also pair electromyography of key muscles within the foot and leg alongside kinetic analysis when investigating minimally shod walking characteristics.

Six months of regular minimal footwear use had no influence on foot morphology or compliance. This was surprising as multiple studies have found differences in foot morphology (D'Août et al., 2009, Shu et al., 2015, Ashizawa et al., 1997, Hollander et al., 2017a, Hollander et al., 2017b) and compliance (Holowka et al., 2018, Kadambande et al., 2006) between experienced and inexperienced minimally shod (or barefoot) walkers. All these comparisons were between habitually conventionally western shod versus habitually minimally shod and/or barefoot walkers so it possible these differences are simply caused by other differences between the populations. However, it is more likely that the observed differences in foot morphology occurred mainly due to the differences in footwear wearing habits between these habitually conventionally western shod and habitually minimally shod and or barefoot participants during childhood, while the foot is relatively more plastic. To solve this ambiguity, further work should be conducted repeating this research project on healthy children as opposed to healthy adults.

The final and third research question was what are the long-term effects of walking in minimal footwear? This research discovered navicular height was greater in the EMS group than the MFA group, suggesting that regular minimal footwear use for periods of time greater than six months can increases navicular height, indicating increased longitudinal arch stiffness. However, the HBM group were found to have significantly lower navicular heights, however this is likely to be caused by population differences as opposed to footwear wearing habits, as African populations have been shown to have lower medial-longitudinal arch heights than European populations (Stolwijk et al., 2013). On top of this the HBM group was small which brings into question the validity of the results. The hypothesis that, conventionally western shod adults will have comparable foot strengths to habitually barefoot and/or minimally shod adults given sufficient minimally shod walking experience, was the only hypothesis within this research that was found to be inconclusive. This was solely due to the limitations associated with the HBM study. The group was too small and not enough biometrics or participant footwear habit history had been collected. As a result, it is likely that the results did not hold enough validity to accept or reject this hypothesis. More in-depth research is required to determine if habitually barefoot and/or minimally shod populations have greater relative foot strength than conventionally western shod populations. This could be as simply as repeating the HBM study with a larger group size and making sure all biometrics and participant footwear habit history are collected.

Changes in navicular height were the only differences in foot function between groups with at least six months of regular minimally shod walking experience. Foot strength per unit mass was not significantly different between the MFA participants that had worn minimal footwear for six months, the EMS group and the San group. This means that six months of regular minimal footwear use is a sufficient time period for habitually conventionally western shod healthy adults foot strength to converge to the foot strength exhibited by habitually minimally shod healthy adults. Foot width between the MFA group and EMS group also showed no differences.

This research found limited differences in gait characteristics caused by regular minimal footwear use for time periods greater than six months. No gait characteristic differences were found between all habitually conventionally western shod participants (of all minimally shod walking experience levels) and indigenously minimally shod participants. This suggests that a time period between six months to two and half years of regular minimal footwear use is a sufficient time period for habitually conventionally western shod healthy adults walking gait characteristics to converge to gait characteristics exhibited by habitually minimally shod healthy adults. This is also supported by the limited changes in MFA minimally shod walking kinematics and kinetics, post-intervention period. However, the reason for the lack of observed differences in gait characteristics could be because cross-population comparisons between groups is limited within this research. Firstly, kinematic and kinetic results were only taken from the MFA group, so this measure for gait characteristics was not available for either the EMS or the indigenous footwear group. Secondly, direct plantar pressure patterns comparisons between groups were not performed in order to avoid the limitations associated with cross-population comparisons. Instead, differences between populations could be inferred based on relative differences between within-population barefoot versus minimally shod comparisons. As previously discussed, this method effectively highlighted differences between MFA and EMS group barefoot versus minimally shod walking centre of pressures. However, spatial plantar pressure distributions are the only results that describe indigenously minimally shod gait characteristics within this research and no participant groups within this study showed differences between minimally shod versus barefoot plantar pressure distributions. Therefore, there were no relative differences to differentiate between groups with different walking experience.

6.1. Limitations

The work produced within this thesis successfully answered the three central research questions. This was a highly ambitious piece of work that ties together participants from around the world and included a six-month longitudinal study with 51 participants (that only dropped to 46 at the end of the intervention period). In particular, the foot strength chapter (chapter three) which encompassed designing, manufacturing, testing, and validating the MPJ.STAR, in addition to maintaining a six-month longitudinal study, resulted in the definitive finding that six months of minimal footwear use increases foot strength. Nonetheless, some other aspects of work within this thesis that could be improved upon. The limitations of this project are discussed below.

Plantar pressure is a large part of this thesis. These measurements can offer powerful insight into foot and ankle biomechanics. Plantar pressure measurements are often used to aid in clinical decisions related to the foot and ankle (Bennetts et al., 2013, Razak et al., 2012). This is because plantar pressure indicates the specific regions where vertical ground reaction forces are acting, and by which magnitude. Pressure plates are made up of a matrix of force sensors each covering a known area. These force sensors are activated when the foot encounters each specific force sensor on the pressure plate. The software used in conjunction with the pressure plate (in this case AMCube) calculates the pressure of each activated load cell as the force reported by each load cell divided by the area each load cell covers. These pressure values are mapped in relation to their respective load cells. This means that throughout the entity of stance phase a complete pressure matrix for the entire foot is completed. Therefore, the location of forces acting on the foot are known throughout stance phase. This means plantar pressures can be used to indicate stressed regions of the foot as well as gait characteristics. In addition to this plantar pressure can offer insight into ankle joint loading. For example, more posterior heel strikes will increase ankle joint moment during heel strike.

Plantar pressure measurements are non-invasive and are quick and easy to collect experimentally, however the analysis requires high technical and methodological knowledge (Deschamps et al., 2015). The results produced are three dimensional given that footprints are generated throughout the stance phase (two spatial dimensions that make up the area and an additional third dimension that makes up time). This makes representing the results challenging. One solution is to take the peak pressures throughout out stance phase to develop peak plantar pressure prints for comparison. This type of analysis will highlight the stressed regions of the foot and was used within this thesis to compare shod walking pressure distributions to barefoot walking. However, this type of analysis does not offer any temporal information. This is the advantage of CoP analysis. CoP analysis is performed by compressing each frame of the developing plantar pressure print to a centroid throughout the stance phase. This can then be used to characterise both the proximal to distal and medial/lateral displacement of force throughout the stance phase therefore offering unique insight into the gait characteristics of the foot during walking. The work presented within this thesis characterised both spatial and temporal plantar pressure patterns (via pSPM and 2D-CoP respectively) to gain insight on the influence footwear has on stress location as well as the gait characteristics of the foot during stance phase.

The greatest challenge associated with plantar pressure analysis within this thesis was attempting to compare the differently shaped pressure signatures between the three walking conditions, as a result of using a pressure plate as opposed to pressure sensitive insoles (which have their own issues). The plantar pressure analysis techniques used within this thesis can align and scale pressure distributions to any desired reference, however manipulating the scale of pressure distributions between intended comparisons eliminates the influence scale has on differences between those conditions. In the case of the results presented within this chapter, conventionally and minimally shod walking plantar pressure distributions were scaled to optimally overlap with the barefoot plantar pressure distributions. This removed the limitation of anatomical alignment between different walking conditions but eliminates any differences that may have existed between walking conditions as a result of scale. This may contribute to why no differences were observed between barefoot and conventionally shod plantar pressure distributions.

To maintain the size differences between walking conditions the 2D-COP analysis within this thesis compared optimally aligned non-scaled plantar pressure characteristics of the walking conditions. However, this also had some limitations. Now, the main issue was the size differences between the walking conditions. The pressure distributions produced by bare feet are smaller than the pressure distributions produced by the same feet minimally and conventionally shod. The optimal scaling transformations used to scale between walking conditions during the pSPM analysis would artificially skew the representation of heel-to-toe transition within the 2D CoP results. Therefore, scaling the shod walking conditions plantar pressures to the barefoot walking plantar pressures was omitted. These walking conditions are still comparable because the pressure experienced by the sole of the shoes is still a relevant indicator of gait characteristics while walking shod. However, there is a limitation when aligning the reference prints used to make the 2D-CoP results from the different walking conditions when they are all differently sized. There is no guarantee that the anatomical regions between walking conditions will overlap. The prints were aligned to the centroid of the average barefoot walking condition, which may not be the reality of where the foot lays inside the shoe. In addition to this, medial/lateral and proximal/distal divisions were defined about the average of the walking conditions average reference print centroid. This is one potential explanation as to why lateral heel strike was not observed in the shod conditions.

Discrete analysis of localised loads is another potential analysis technique that appears it could have been used to overcome the scaling limitation stated above. This analysis method involves predefining pressure regions based on discrete anatomical regions (e.g., Hallux, Heel, etc.) and summing up the pressures within these regions for comparisons (Bennetts et al., 2013). However, this analysis method was not incorporated into this thesis because shod walking plantar pressure distributions measured by pressure plates do not truly relate to discrete anatomical regions. The sole material of any given footwear between the pressure plate and the bare foot skews the pressure distribution of discrete anatomical regions and in many cases makes the discrete anatomical regions unrecognisable and therefore undefinable. This method could be used for shod and barefoot plantar pressure comparisons if the shod walking plantar pressure measurements were recorded by plantar pressure sensitive insoles. However, if this were the case the limitation relating to the pressure analysis techniques used with this thesis would no longer exist. In conclusion, there is no ideal analysis method for comparing shod and unshod walking plantar pressures that are recorded with a pressure plate. Future studies intending to compare barefoot and shod walking plantar pressure results could use pressure sensitive insoles. However, this has its own set of technical complications, and the only perfect solution would be a very flexible and thin "pressure sock" but to the best of our knowledge this is not commercially available. A potential future study is discussed in more detail in the future research section of this chapter.

In chapter five, the Ghent foot model was used for placing the markers on the participants. This model is a highly detailed marker set that allows for novel insights and observations into foot kinematics. This model was chosen to try and gather as much data as possible regarding foot kinematics. However, the experimental setup was such that the markers on the feet and the rest of the body were recorded at the same time. This meant camera position had to be carefully selected so that it was close enough to reliably record the small markers used for the Ghent foot model while still capturing the whole body and as much of the walkway as possible. In an attempt to capture as much of the walkway as possible it is likely that the cameras were placed slightly too far away to reliably capture the Ghent foot model markers. This meant some of the recordings had unreliable data coming from the foot model. This meant some of the participants did not have any usable complete foot data. The decision was made to simplify the foot kinematic analysis to only include transverse arch dynamic compliance, longitudinal arch dynamic compliance and dynamic forefoot spread, so that more participants could be included in the analysis. In hindsight, the use of the Ghent foot model was probably overly ambitious. Although it provides valuable data, the camera and lab set up to accurately record the foot model is different to a full-body recording. Further studies should consider the use of the Ghent foot model only with a camera set up specific for foot kinematic recording.

Lastly, all the kinematic trials were performed inside the gait lab, at the University of Liverpool. The floor of the lab has compliant and had elastic properties greater than the substrates that people normally walk on. In effect, the gait lab floor was providing slight cushioning that has the potential to influence gait characteristics for all walking conditions. For barefoot walking, enough floor cushioning could cause similar kinematics to that of shod walking, although it is unlikely that the characteristics of the floor would have such great impact. In the case of the conventionally shod condition, the floor characteristics could influence gait such that participants would display a gait more akin to that of an overly cushioned walk, such as walking on foam. However, it does not appear that the floor had a major impact on the participants' gait, as evidenced by the results that show clear differences between walking conditions. This is likely due to all participants of all walking conditions being tested under the exact same conditions. Nonetheless, the data collected in for this study may not be an accurate representation of the gait that people display during normal life, due to the substrate, and potentially due to the controlled lab environment.

6.2. Future research

The work within this thesis will inform future research regarding footwear and foot function. Given the results found, future research should focus on the following areas. One area of interest would be to move this type of study outside of the lab environment. Testing participants outside of the lab environment (often referred to as "biomechanics in the wild") has become more prevalent in recent years (Foulsham et al., 2011, Hillel et al., 2019, Thomas et al., 2020a, Thomas et al., 2020b). Studies have shown gait characteristics measured within the lab are not a perfect representation of daily gait characteristics (Hillel et al., 2019, Toda et al., 2020). Additionally, advances in technology are making "biomechanics in the wild" more accessible (Storm et al., 2016, Storm et al., 2018). Future studies could replicate the plantar pressure and kinematics experiments represented within this thesis outside of the lab in order to better characterise the daily influence minimal footwear has on the users' biomechanics. This would also give the opportunity to test individuals not only under different environments, but different substrates.

Another area for future research should be measuring shod walking plantar pressures with pressure sensitive insoles. The use of pressure sensitive insoles would allow for a direct measurement of foot pressures, and this has indeed extensively been used in non-minimal footwear. However, the use of pressure insoles would be a challenge in the barefoot condition and would require some form of gluing or use of a sock (e.g. Burnfield et al. (2004)), potentially affecting results. The use of insoles in the shod condition and of a plate in the barefoot condition is not preferable if a direct comparison (as in this study), without technical confounding factors, is to be made. Therefore, the first step should be should be to test the conventionally shod and minimally shod walking with pressure sensitive insoles while walking over a pressure mat simultaneously. This would establish how well the pressure experienced by a given footwear sole relates to the pressure experienced by the foot within the shoes. I expect minimally shod walking would reveal high correspondence between both pressure measurements given that minimal footwear soles are very thin. Whereas conventionally shod walking insole and mat pressure recordings would show significantly less correspondence. Another potential study could be designing a pressure sensitive sheet which can also be cut out to make pressure sensitive insoles. This way participants could walk over the sheet while barefoot and use tailored pressure sensitive insoles while walking in shod conditions. This would allow all the conditions to be a true representation of themselves while also allowing good correspondence between the results given that the plantar pressure measuring technology is constant throughout.

Lastly, the data collected in this thesis has been divided into only two groups. I expect future research to change this practise and focus on a more nuanced way of classifying participants. For example, dividing by gender, by arch height, foot size, BMI, etc, would potentially highlight results obscured by the varied groups presented here.

6.3. Conclusion

Overall, the non-restrictive design features of minimal footwear allow for closer gait characteristics to barefoot walking than conventional footwear while still providing protection from the environment. Changes to minimally shod walking gait characteristics as a result of experience are very limited, therefore there is no learning curve for healthy adults transiting to this footwear with the intention of using the footwear for daily activity. Finally, regular, and consistent walking in minimal footwear allows habitually conventionally western shod adults to build up and maintain naturally strong feet.

6.4. References

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7. Appendices

7.1. Appendix A: Chapter 2 Supporting Material

Barefoot, minimally and conventionally shod walking plantar pressure data was collected from 13 participants. The differences between the barefoot and minimally shod conditions compared to the conventionally shod condition are clear just by simply visual inspection of the 1st print (out of 6 trials or more) per condition for each participant (Figure 7.1). It can be seen that the barefoot and minimal prints many similar characteristics. They both have a clear toe, ball, midfoot and heel region in all the prints displayed in these conditions. They also have a very comparable shape. The conventional condition on the other hand does not have these clearly defined regions or a similar shape. And where the barefoot and minimal conditions are consistent throughout the participants within their respective conditions, the conventional condition is not. The highly varied nature of the prints displayed proves how variable walking in conventional footwear is.

Pedobarographic Statistical Parametric Mapping was applied to the barefoot vs. conventionally shod conditions in the western subset, and the results can be seen in Figure 7.2. The barefoot average relative pressure distribution has three distinct pressure points, located at the hallux, heel and most notable, the ball of the foot. The conventionally shod average relative pressure distribution has one notable pressure point at the heel that is lower than the relative pressure experienced at the ball of the foot, meaning that pressure is more evenly distributed in conventional footwear. This does not mean that walking in conventional footwear reduces pressure as the comparison is made between relative pressure distributions and conventional footwear increases the area pressure can be dissipated through during impact. In contrast with the visual correspondence, the pSPM analysis shows no significantly different regions between the two conditions. This is likely due to two factors; One, the small sample size and, two, the level of variation in the conventional condition. These factors combined makes it likely that the variation within the conventional condition hide any statistically significant difference between the two conditions, despite the clear visual differences between the averages of the two conditions. This is just speculation however, further work is required with a larger subset, in order to determine any significant differences between conventionally shod walking and barefoot walking.

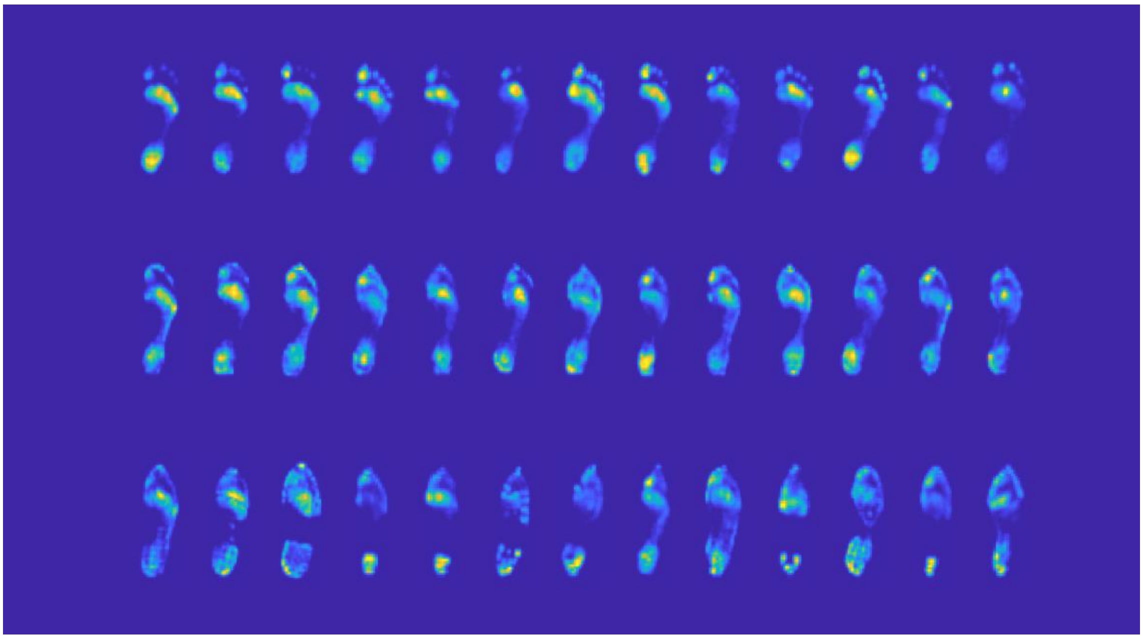

Figure 7.1: Normalised max pressure prints from the 13 Belgium participants that walked barefoot, minimally shod and conventionally shod. Each column is a participant and each row is a condition (top row: barefoot; middle row: minimal; bottom row: conventional).

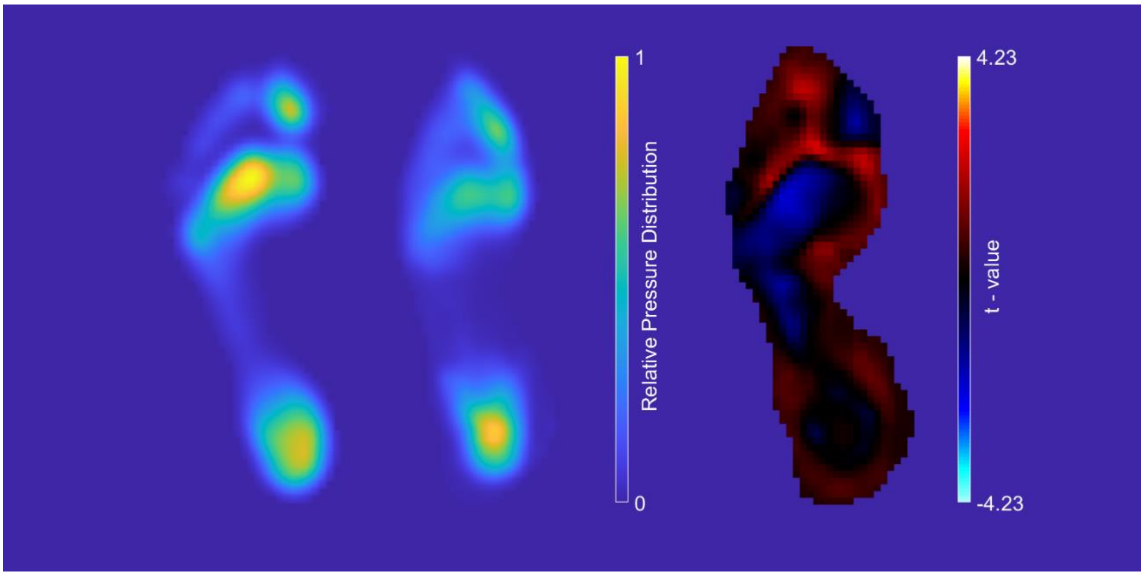

Figure 7.2: Comparison of relative pressures for the Belgium participants walking barefoot and conventionally shod (13 barefoot and conventionally shod participants with 77 trials and 81 trials for barefoot and shod groups respectively). From left to right: Average barefoot pressure; Average shod pressures; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.

7.2. Appendix B: Participant Activity Log

This questionnaire is confidential. The information you provide will be stored in a file on a private data storage device that is password protected. Only the principal investigator – Dr Kristiaan D'Aout and student investigator – Mr Rory Curtis will have access to this file. No one else will see your information and neither Dr D'Aout nor Mr Curtis will mention or distribute the information provided.

Please state the Week number in the box below:

WEEK	1)

- How many hours did you wear your prescribed shoes for each day this week?

Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday	
	Hrs		Hrs		Hrs		Hrs		Hrs		Hrs		Hrs

- How many hours sleep do you perceive you achieved each night this week?

Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday	
	Hrs		Hrs		Hrs		Hrs		Hrs		Hrs		Hrs

- Have you changed footwear since last week?

Yes/No

If "Yes", please describe the new footwear and the day you changed to them

- Have you started any new activities since last week?

Yes/No

If "Yes", please describe your new activity.

- Have you made any large changes in your diet since last week?

Yes/No

If "Yes", please describe your new diet.

- What is the maximum perceived discomfort in your feet you have experienced this week, expressed as a number from 0 – 4. Where; 0 = none, 1 = slight, 2 = some, 3 = considerable, 4 = intense.

0	1	2	3	4

If your answer was 1 or more please describe your discomfort.

7.3. Appendix C: Future Footwear Questionnaire

This questionnaire is confidential. The information you provide will be stored in a file on a private data storage device that is password protected. Only the principal investigator – Dr Kristiaan D'Aout and student investigator – Mr Rory Curtis will have access to this file. No one else will see your information and neither Dr D'Aout nor Mr Curtis will mention or distribute the information provided.

SECTION A – PERSONAL DETIALS

1. Personal Details – Please fill in your personal details.

Name	
Date of birth	
Sex	
E-mail Address	

SECTION B – FOOTWEAR

2. How many hours a week do you wear the following types of footwear? Please note if you wear any of the footwear listed below, but on average of less than an hour a week please answer "0"Hrs along with footwear types you have never worn before.

Trainers (fashionable)		Hrs
Trainers (sports shoes)		Hrs
Formal shoes		Hrs
Minimal footwear		Hrs
Heels		Hrs
Plimsolls		Hrs
Slippers		Hrs
Walking Boots		Hrs
Sandals		Hrs
Flip-Flops		Hrs
Other		Hrs

3. If you wear “Other”, please describe the footwear in the space provided below:

4. Please describe the Shoes your that you wear the most. Please include their brand.

5. How long have you had the shoes you described in question 4 for?

6. How long have you worn this type of footwear in general for?

7. If you answered less than two years to Question 6 please state the type of shoes you wore the most before you made the change.

SECTION C – ACTIVITY

8. On average, how many hours a week would you say you are actively on your feet (e.g. walking, running, etc.)?

	Hrs

9. Please place one tick next to the statement you believe best describes your occupation in the table below:

Sit down 9 – 5 job in the office	
Sit down most of the time and sometimes move around performing errands	
Sit down sometimes and move around performing errands sometimes	
Moving often and sitting down sometimes	
Always on your feet	

SECTION D – HEALTH

10. Have you injured either your legs or feet in the last 6 months?

YES / NO

11. If you answered "yes" to Question 10 please describe your injury.

12. Do you have any of the following conditions that may affect your ability to take part in this study?

Bone marrow Edema	
Hallux Valgus, Varus, Rigidus or Limitus	
Plantar fasciitis	
Osteoarthritis in the lower limb	
Rheumatoid Arthritis in the lower limb	
Heart Conditions	
Blindness	
Under 4'10"	
Missing lower limb/s	
Foot size 3 or under	
Foot size 13 or over	
Other	

13. If you answered "Other" to question 12 please describe your condition/s.

7.4. Appendix D: Kinematic Marker Set-up

IACD - Evolutionary Morphology and Biomechanics

Whole body standard marker set

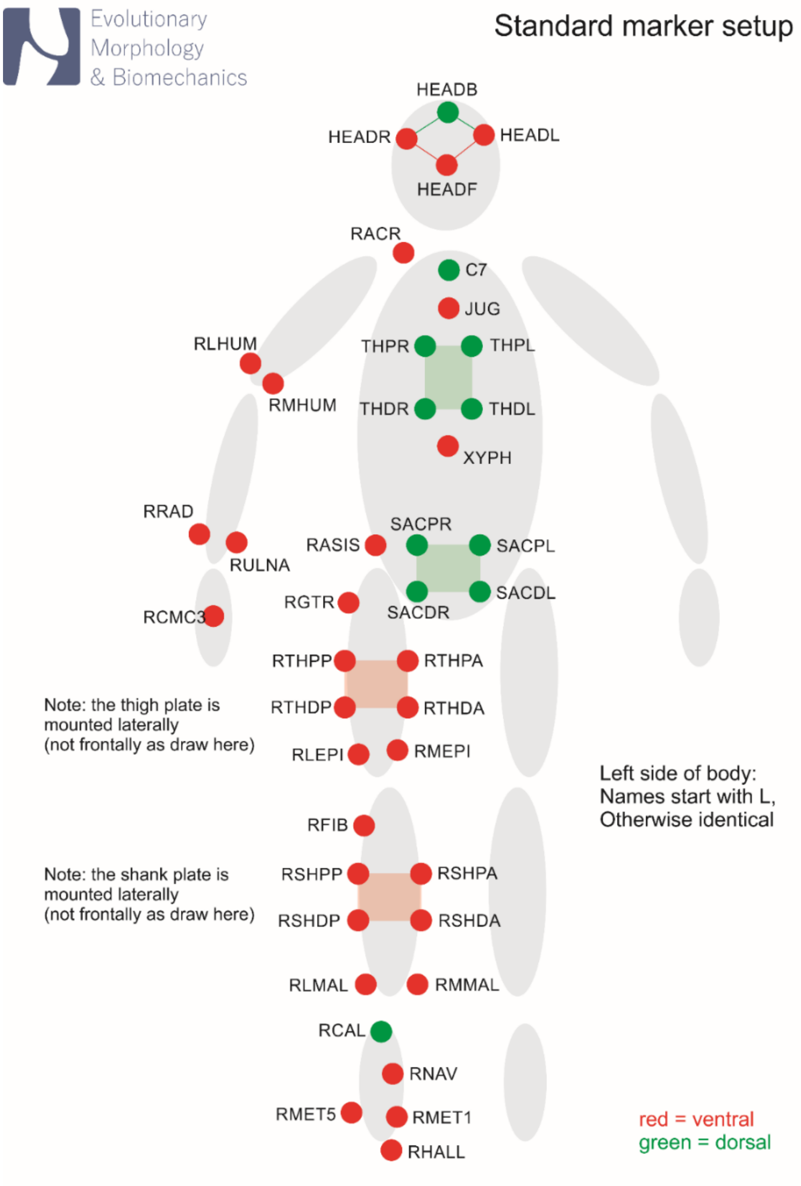

Figure 7.3: EMB standard whole body marker set.

Total: 67 markers (incl. plates and straps). 39 loose markers and 7 plates/straps.

Trunk: 5 markers, 1 plate	
LACR RACR	acromion
JUG	jugular notch
XYPH	xyphisternal joint (on strap)
C7	spine of the 7th cervical vertebra
THPL THPR THDL THDR	Thorax plate proximal/distal and left/right – worn dorsally (high)

Head: 1 strap	
HEADF HEADB HEADL HEADR	Hat or band with four markers (1 front, 1 back, 2 side)

Pelvis: 2 markers, 1 plate	
LASIS RASIS	anterior superior iliac spine
SACPL SACPR SACDL SACDR	Sacrum plate proximal/distal and left/right – worn dorsally (low)

Upper leg: 3 markers, 1 plate (x2)	
LGTR RGTR	greater trochanter
LLEPI RLEPI	lateral epicondyle
LMEPI RMEPI	medial epicondyle
LTHPA LTHPP LTHDA LTDP RTHPA RTHPP RTHDA RTDP	L and R THIGH plates: proximal/distal and anterior/posterior

Lower leg: 3 markers, 1 plate (x2)	
LFIB RFIB	fibular head
LLMAL RLMAL	lateral malleolus
LMMAL RMMAL	medial malleolus
LSHPA LSHPP LSHDA LSHP	L and R SHANK plates: proximal/distal and anterior/posterior

RSHPA RSHPP RSHDA RSHDP	

Foot: 5 markers (x2)	
LCAL RCAL	tuber calcanei
LMET5 RMET5	Metatarsal V head
LMET1 RMET1	Metatarsal I head
LHALL RHALL	hallux (tip)
LNAV RNAV	navicular

Arms: 5 markers (x2)	
LLHUM RLHUM	lateral humeral epicondyle
LMHUM RMHUM	medial humeral epicondyle

LULNA RULNA	ulnar head (distal epiphysis)
LRAD RRAD	radial head (styloid process)
LCMC3 RCMC3	carpometacarpal joint III

Optional markers (not normally used)	
Ghent Foot Model	A published marker set (De Mits et al, 2012, J Orthop Res) for multi-segmented foot studies

Thorax plate and sacrum plate (right).

Try to align SACPL and SACPR (two top markers) to correspond with the two PSIS.

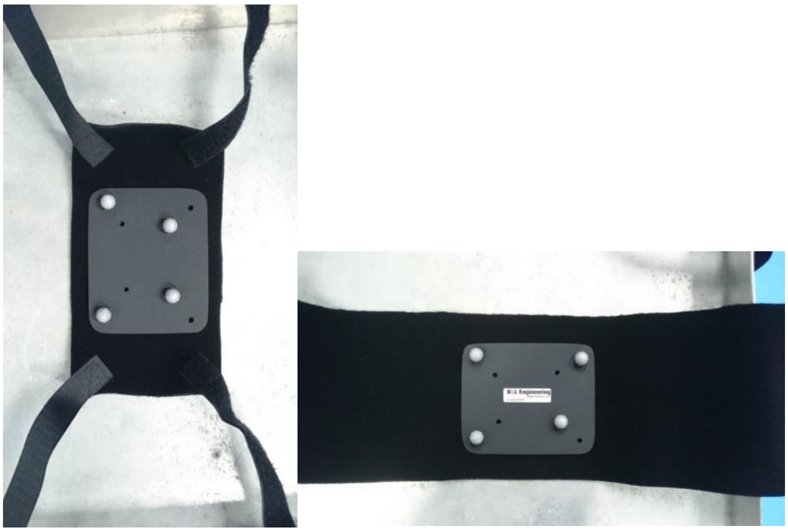

Figure 7.4: Thorax plate (left) and sacrum plate (right).

The Ghent Foot Model

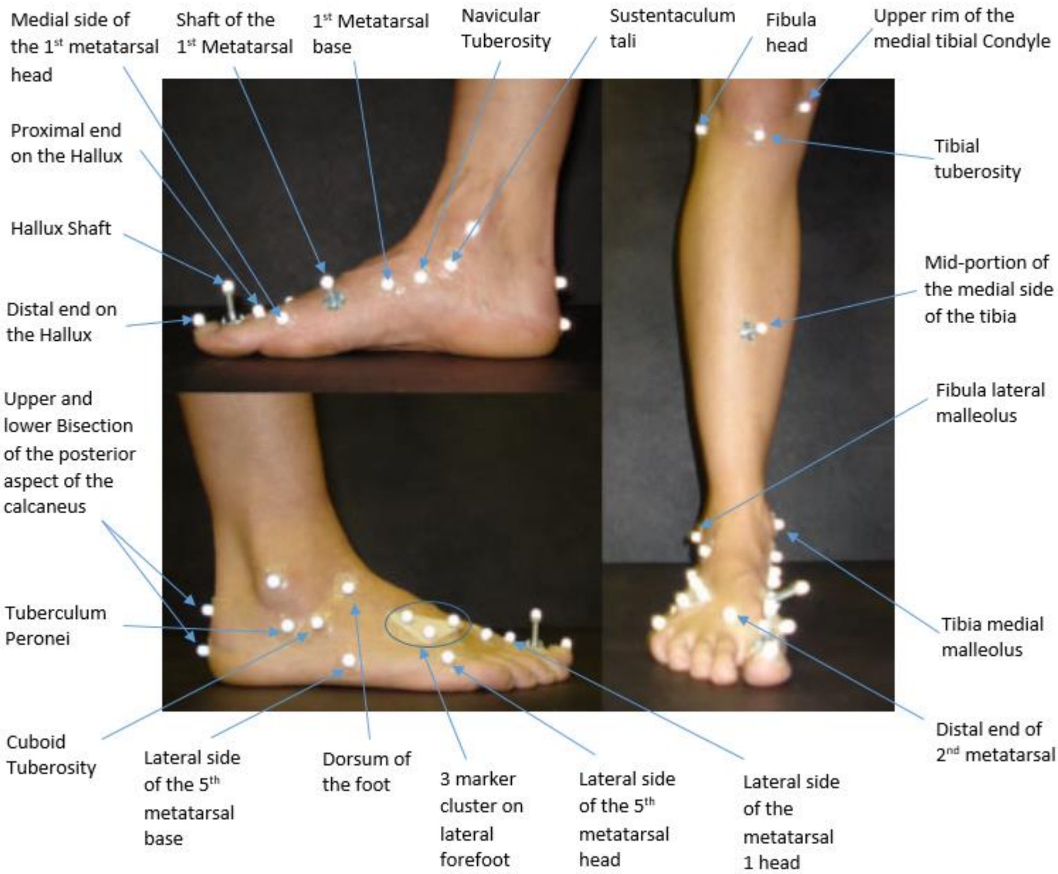

Figure 7.5: Annotated Ghent Foot Model.

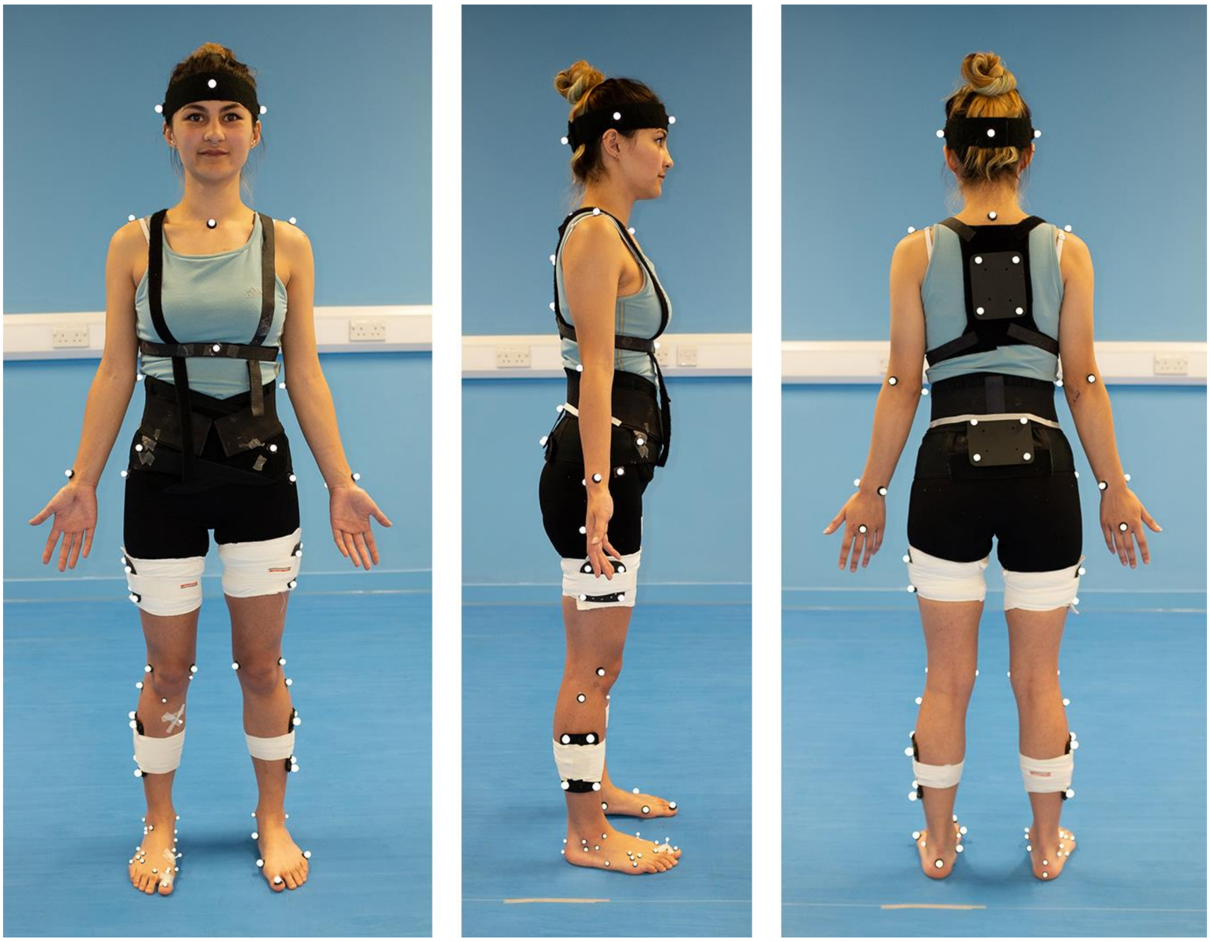

Figure 7.6: Study participant demonstrating the standard marker set and, on the right foot, the Ghent Foot Model.

7.5. Appendix E: Supporting Material for chapter 5

Table 7.1: Control group spatial and temporal variables for the intervention participants while walking barefoot, conventionally shod and minimally shod, pre and post intervention period. "B", "C" and "M" represent barefoot, conventionally shod and minimally shod respectively.

Spatial – Temporal Variables	Control Group					
	Pre-Intervention Period			Post-Intervention Period		
	B (n=22)	C (n=21)	M (n=22)	B (n=22)	C (n=21)	M (n=22)
Speed(m/s)	1.44 ±0.17	1.47 ±0.18	1.44 ±0.17	1.39 ±0.14	1.43 ±0.14	1.43 ±0.14
Stride Width (m)	0.111 ±0.023	0.116 ±0.024	0.117 ±0.027	0.101 ±0.024	0.112 ±0.026	0.11 ±0.023
Stride Length (m)	1.47 ±0.14	1.54 ±0.15	1.51 ±0.14	1.45 ±0.12	1.54 ±0.13	1.51 ±0.12
Stride Freq. (Hz)	0.98 ±0.049	0.95 ±0.052	0.96 ±0.047	0.96 ±0.052	0.93 ±0.043	0.95 ±0.042
Duty Factor	0.649 ±0.013	0.652 ±0.013	0.652 ±0.011	0.653 ±0.010	0.653 ±0.013	0.652 ±0.010

Table 7.2: Control group pre vs. post intervention period spatial and temporal metric comparisons between walking conditions. "B", "C" and "M" represent barefoot, conventionally shod and minimally shod respectively. Post-intervention period percentage change (%) is shown for each spatial-temporal metric. P-values (p) were derived from paired t-tests for each pre vs. post walking condition comparison respectively. Cohen's d values (d) were calculated for spastically significant results. Very small, small, medium, large, very large and huge effect sizes are represented by Cohen d values less than 0.01, 0.2, 0.5, 0.8, 1.2 and 2 respectively.

Control Group Pre vs. Post Spatial Temporal Metric Comparisons									
	B			C			M		
	%	*p*	*d*	%	*p*	*d*	%	*p*	*d*
Speed	-2.86 ±7.18	**0.042**	0.32	-1.98 ±8.74	0.135	-	-0.46 ±7.2	0.54	-
Stride Width	-8.5 ±14.1	**0.016**	0.53	-2.88 ±12.46	0.278	-	-4.29 ±15.82	0.144	-
Stride Length	-0.97 ±5.78	0.309	-	-0.23 ±6.24	0.709	-	0.57 ±5.14	0.739	-
Stride freq.	-1.93 ±3.56	**0.014**	0.54	-1.84 ±4.23	**0.03**	0.47	-1.08 ±3.62	0.14	-
Duty Factor	0.63 ±1.77	0.103	-	0.14 ±1.99	0.776	-	0.01 ±1.33	0.993	-

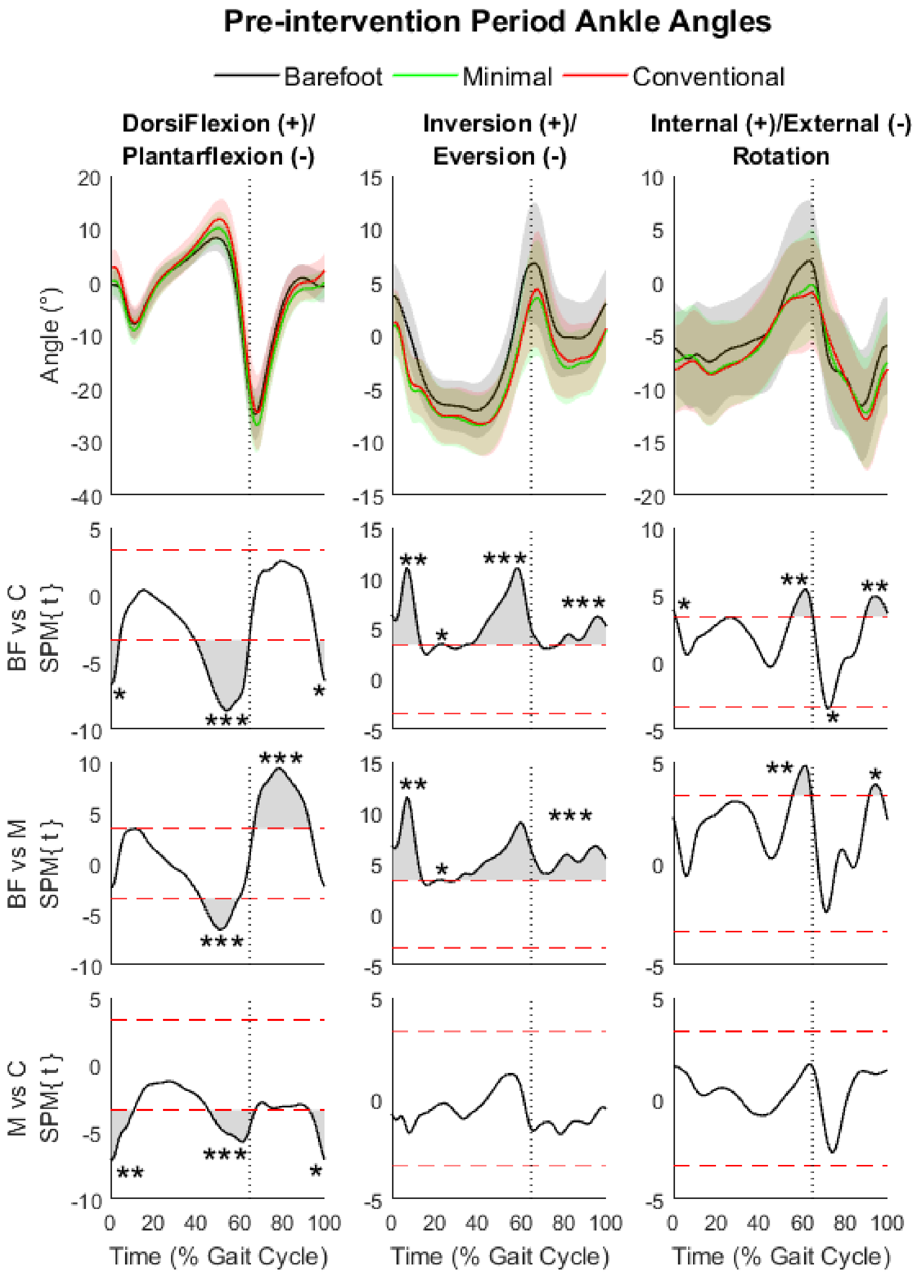

Figure 7.7: Pre-intervention participants' ankle angles in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=50) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

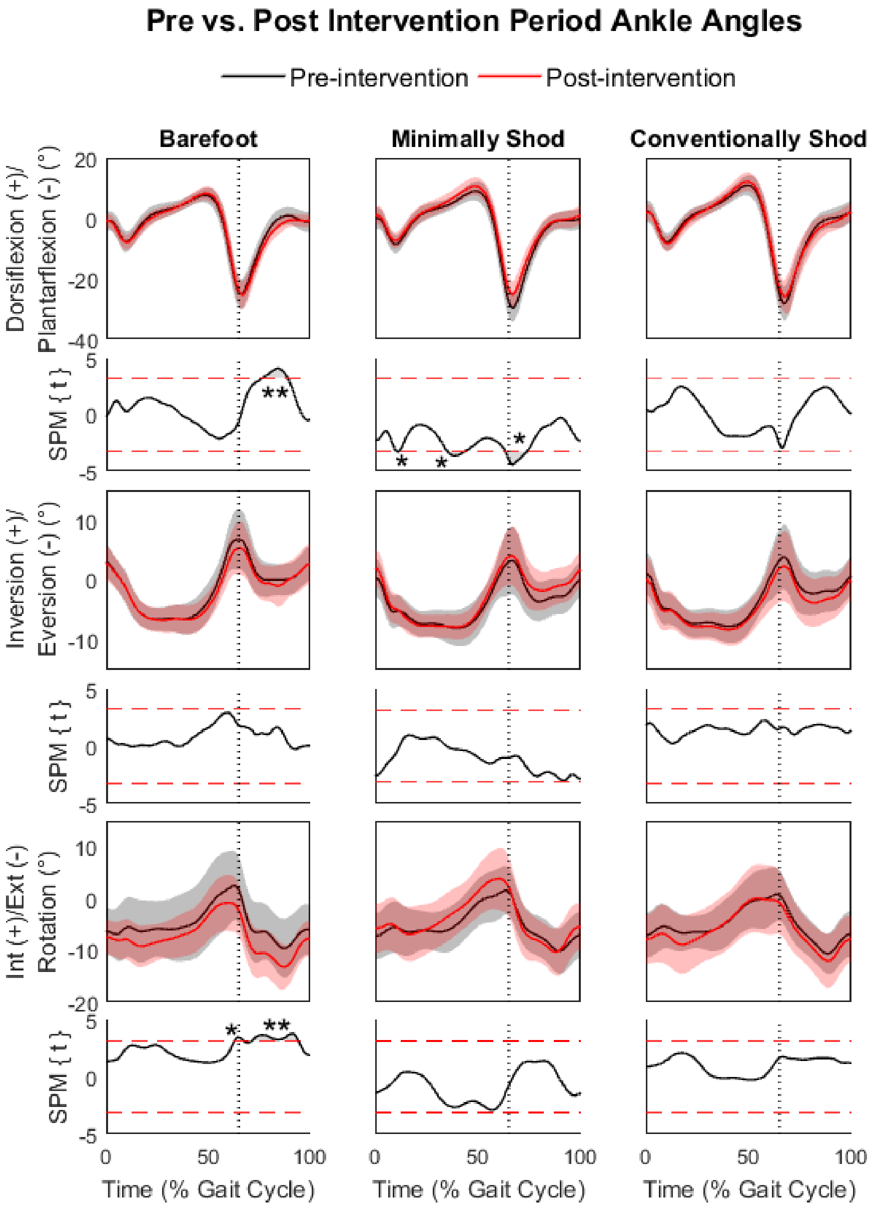

Figure 7.8: Intervention participants' pre and post intervention period ankle angles in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

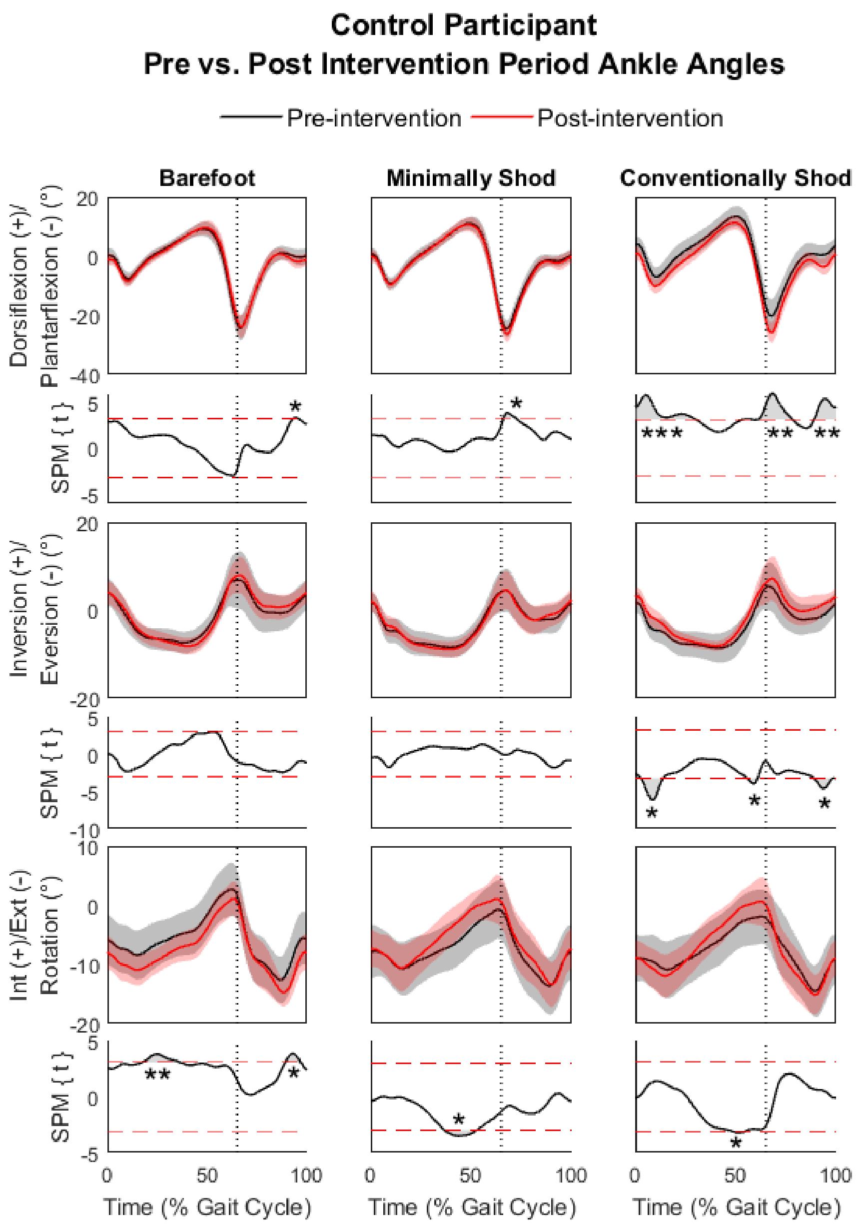

Figure 7.9: Control participants' pre and post intervention period ankle angles in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=23), minimally shod (M; n=22) and conventionally shod (C; n=23). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

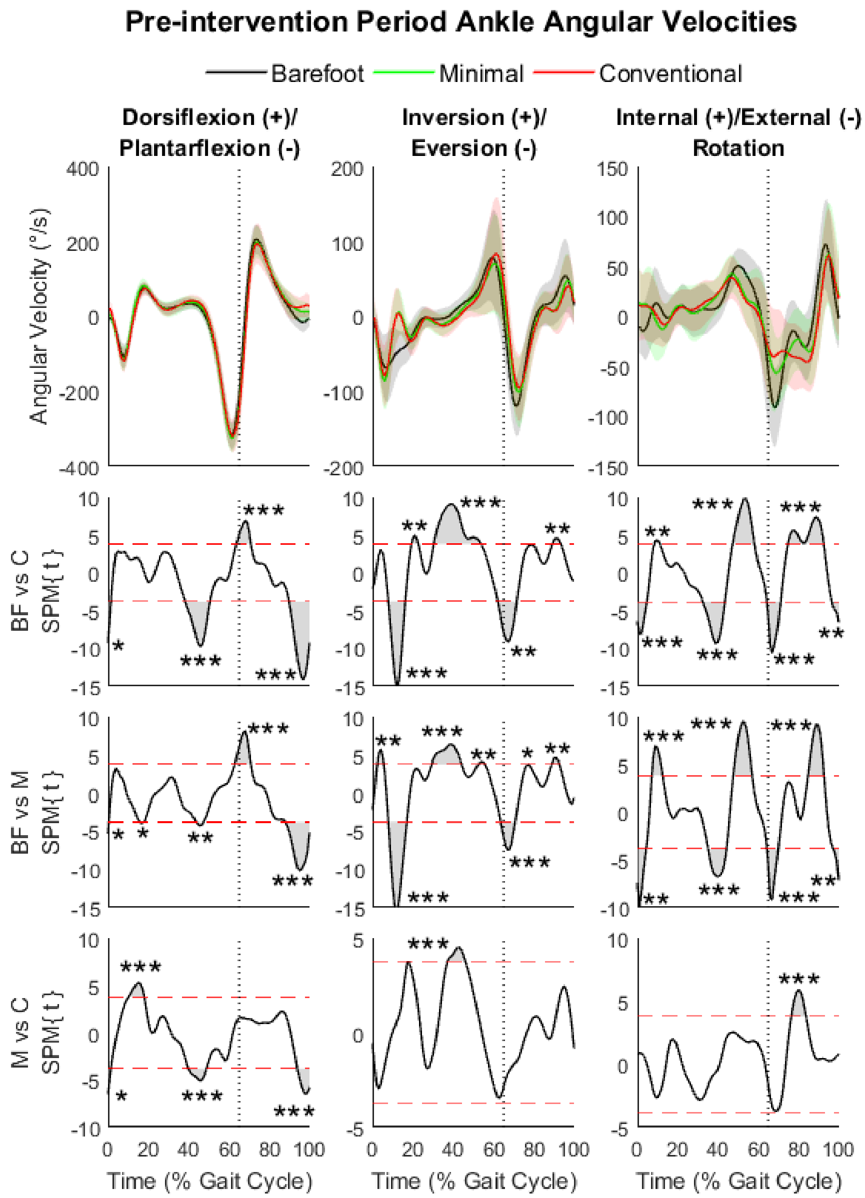

Figure 7.10: Pre-intervention participants' ankle angular velocities in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=50) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

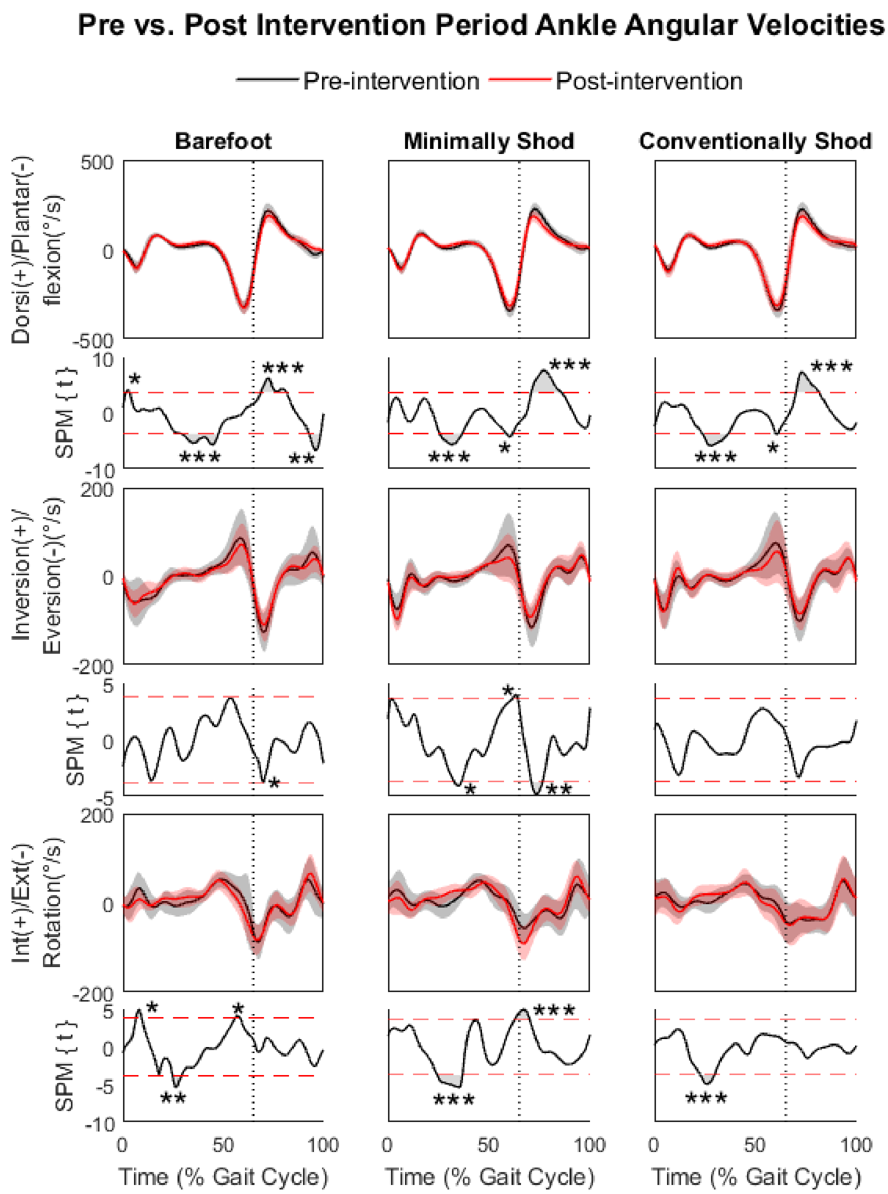

Figure 7.11: Intervention participants' pre and post intervention period ankle angular velocities in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

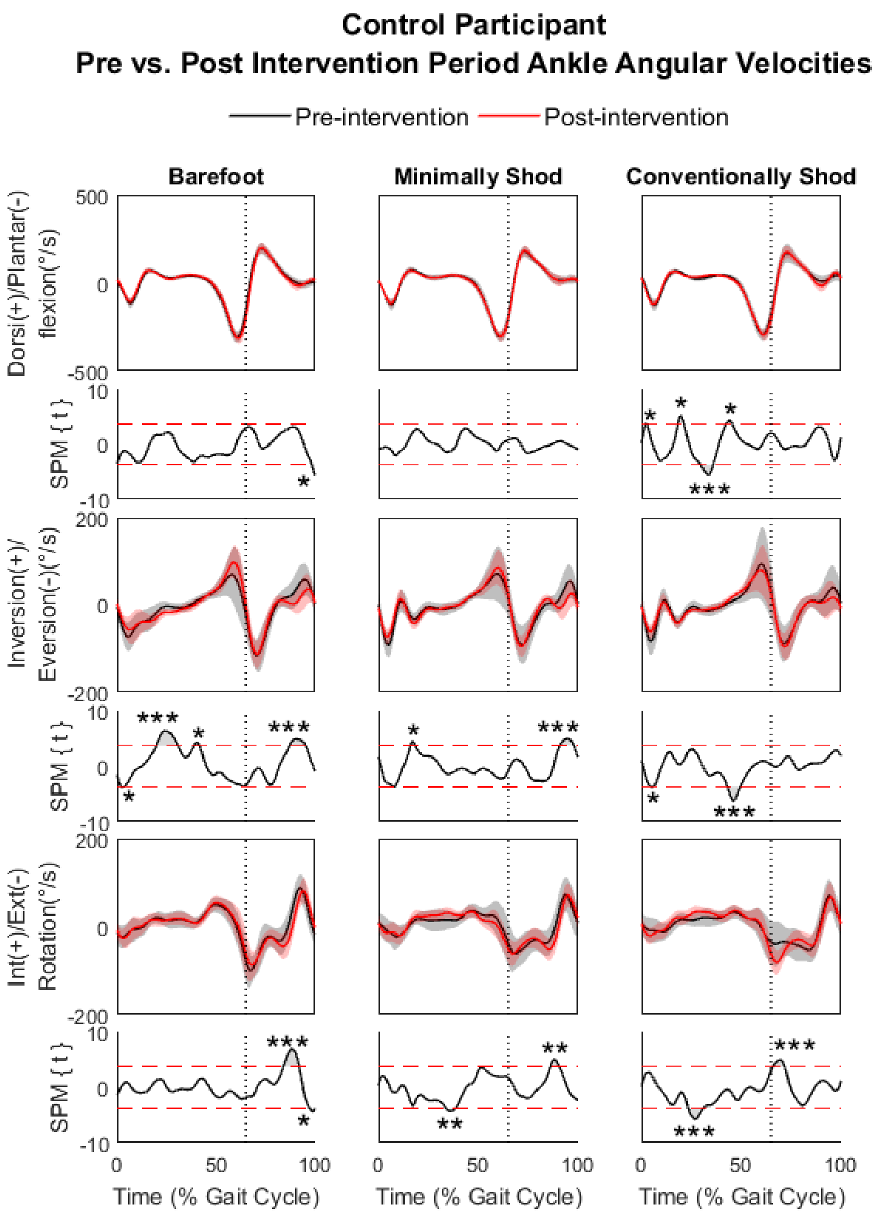

Figure 7.12: Control participants' pre and post intervention period ankle angular velocities in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=23), minimally shod (M; n=22) and conventionally shod (C; n=23). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

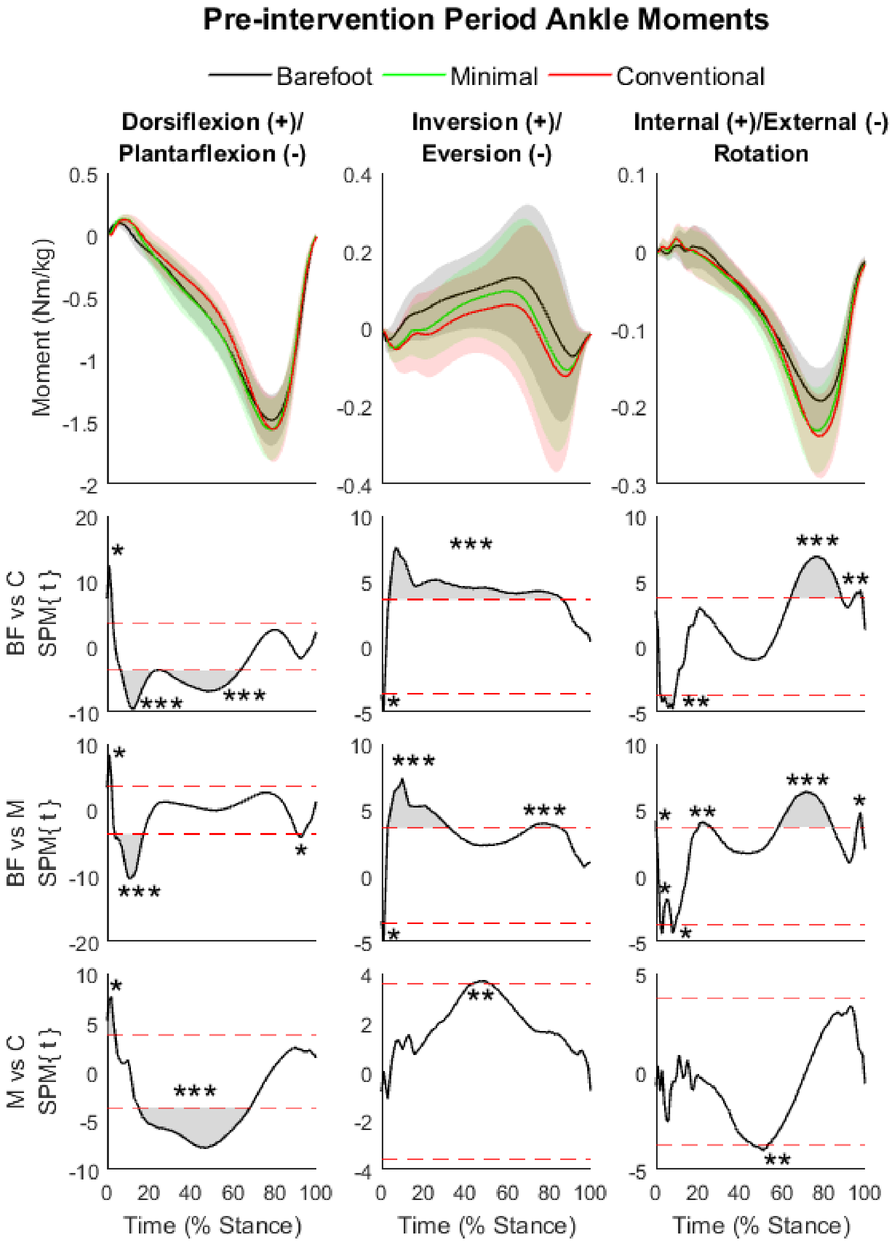

Figure 7.13: Pre-intervention participants' ankle moments in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=40) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

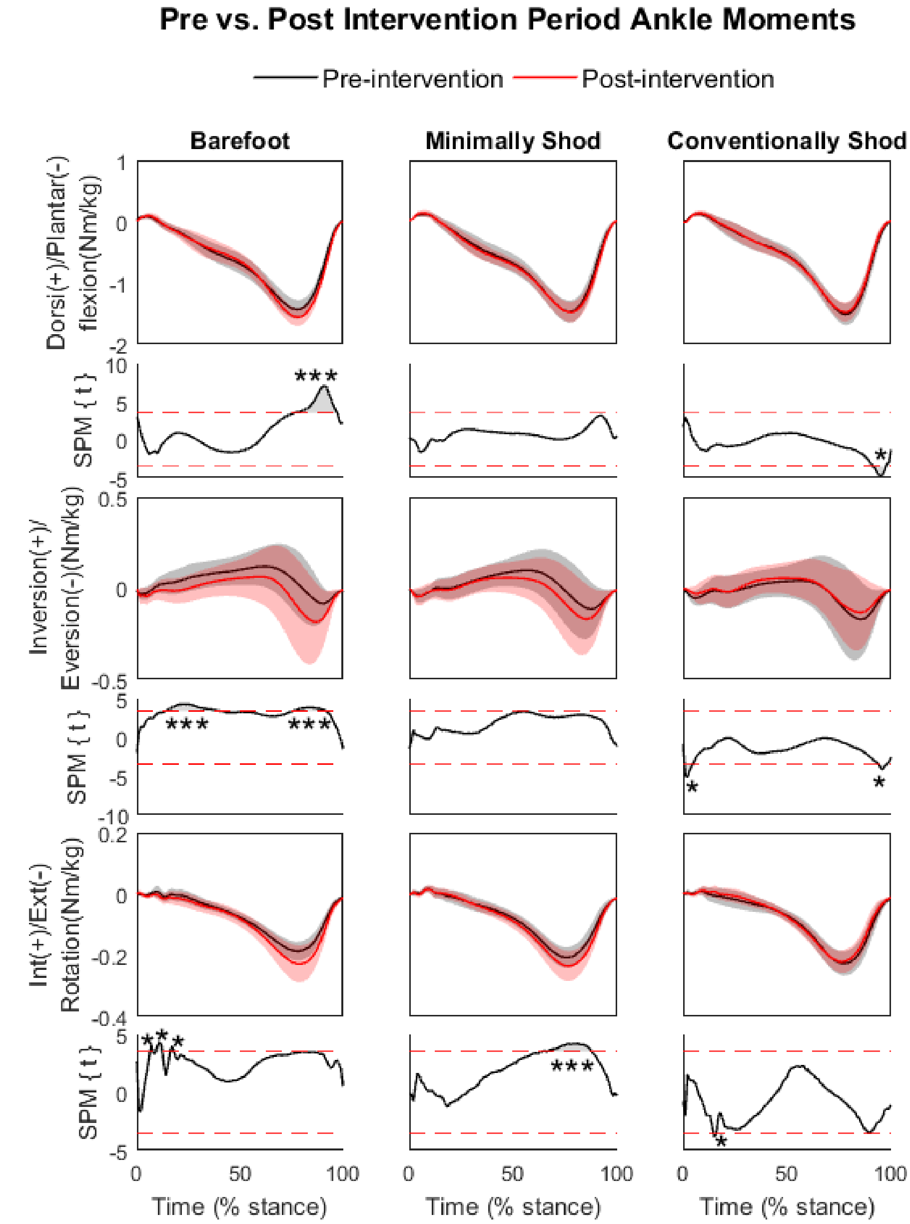

Figure 7.14: Intervention participants' pre and post intervention period ankle moments in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=21) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

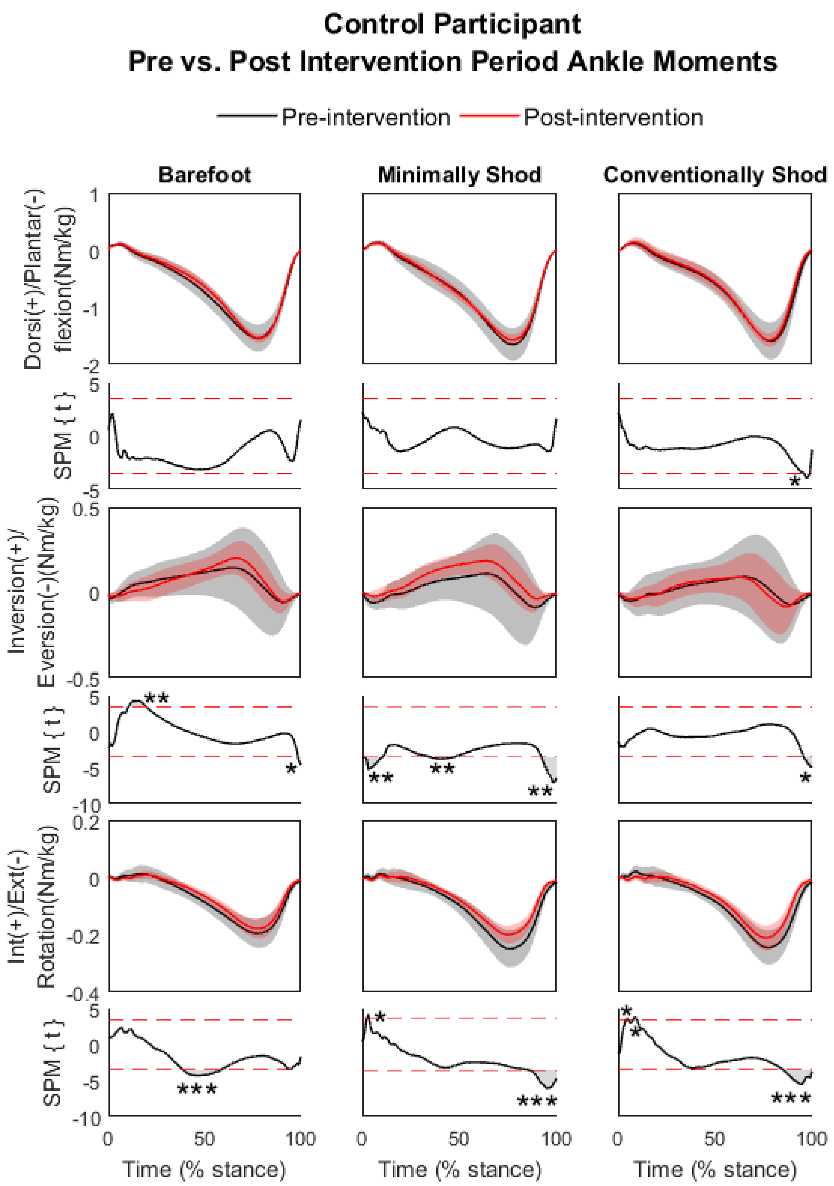

Figure 7.15: Control participants' pre and post intervention period ankle moments in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=19), minimally shod (M; n=18) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

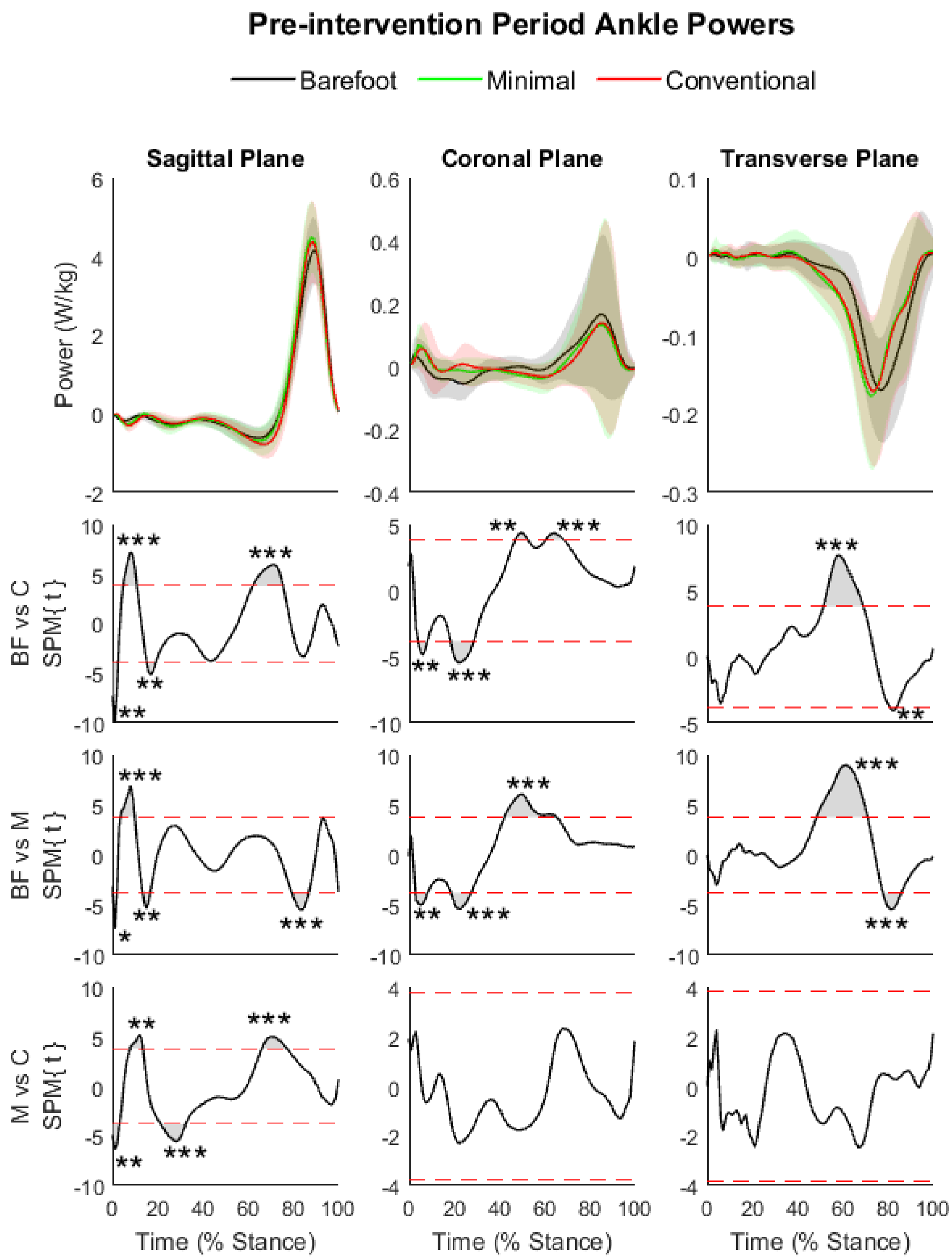

Figure 7.16: Pre-intervention participants' ankle angles in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=40) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

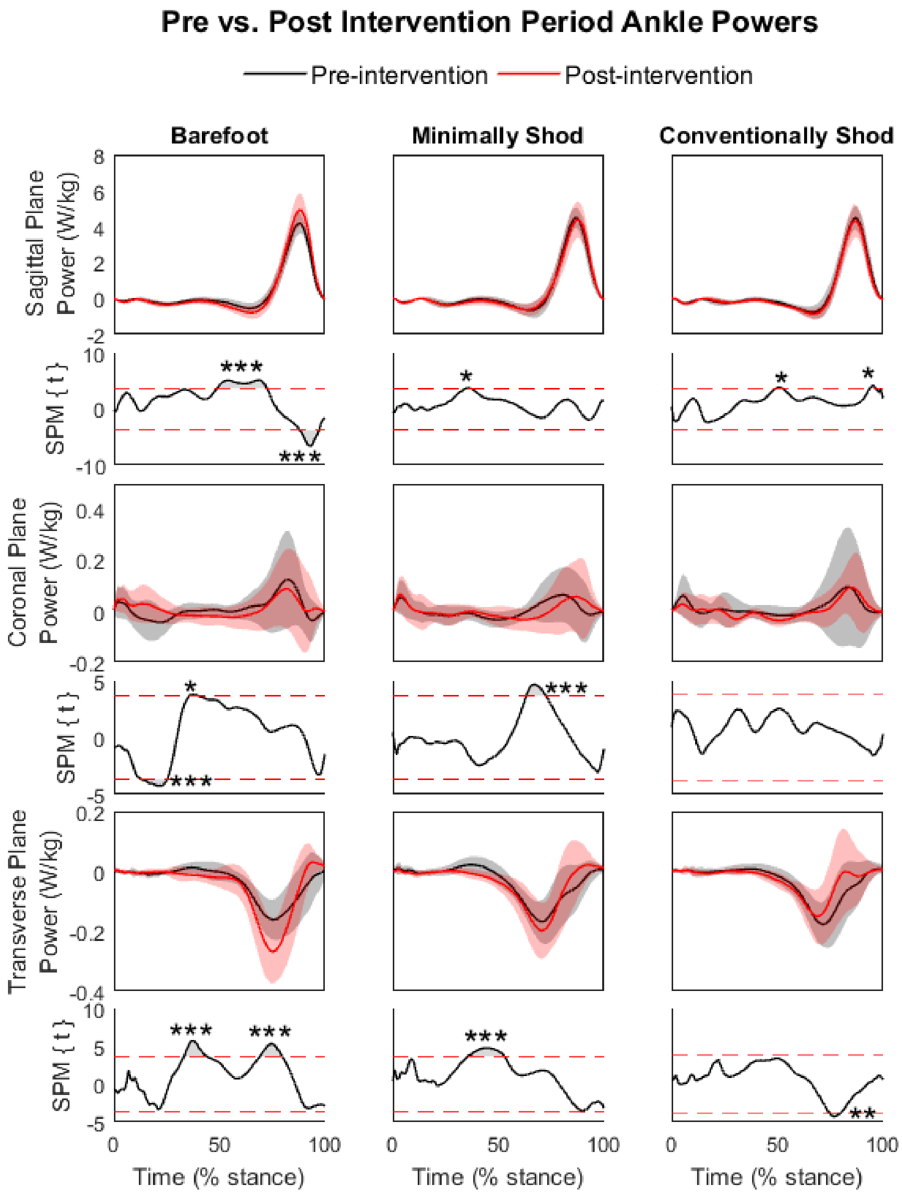

Figure 7.17: Intervention participants' pre and post intervention period ankle powers in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=21) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

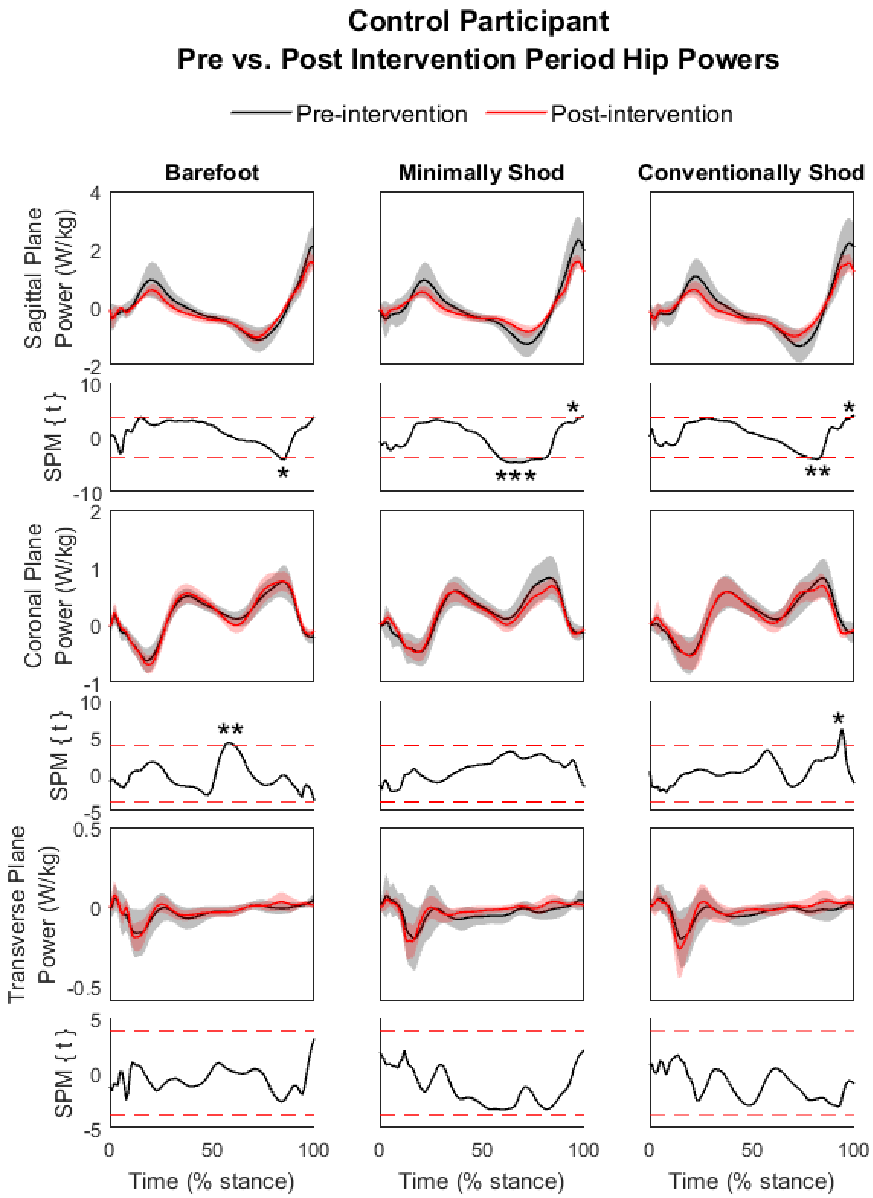

Figure 7.18: Control participants' pre and post intervention period ankle powers in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=19), minimally shod (M; n=19) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

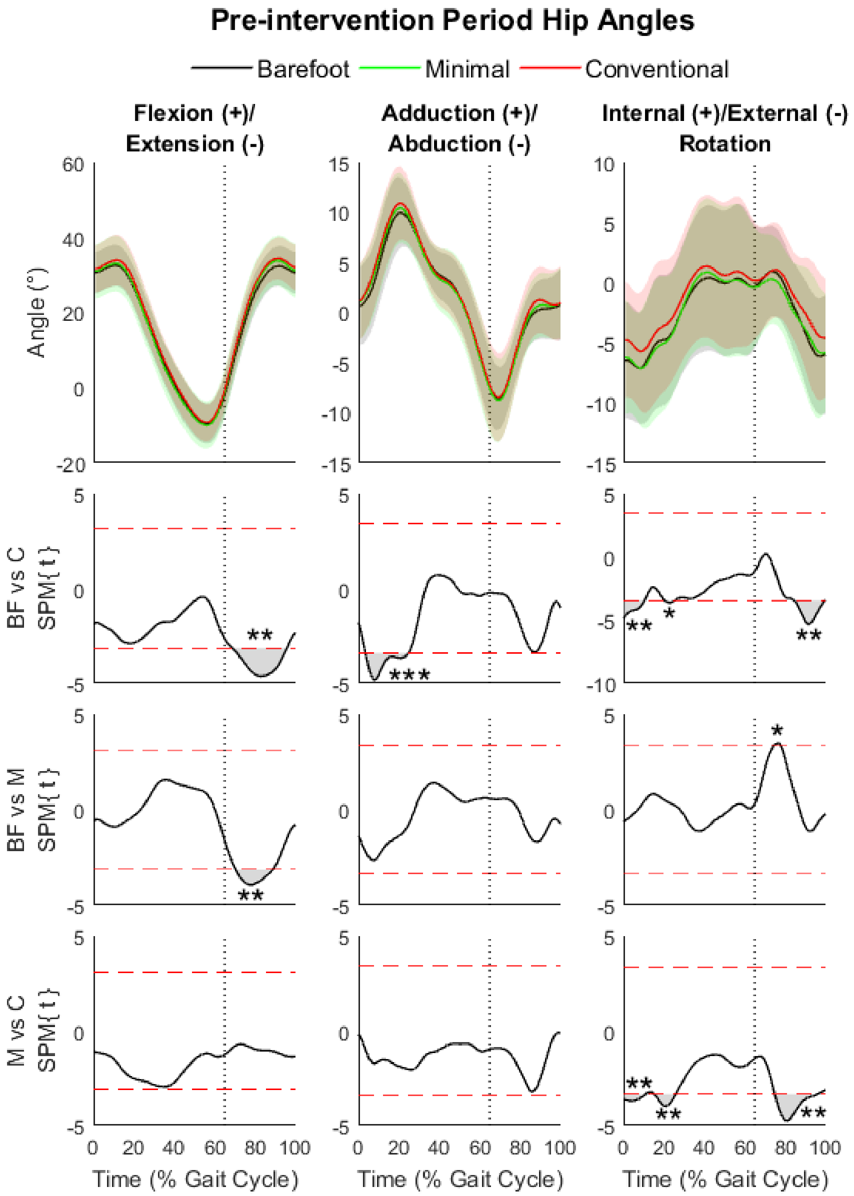

Figure 7.19: Pre-intervention participants' hip angles in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=50) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

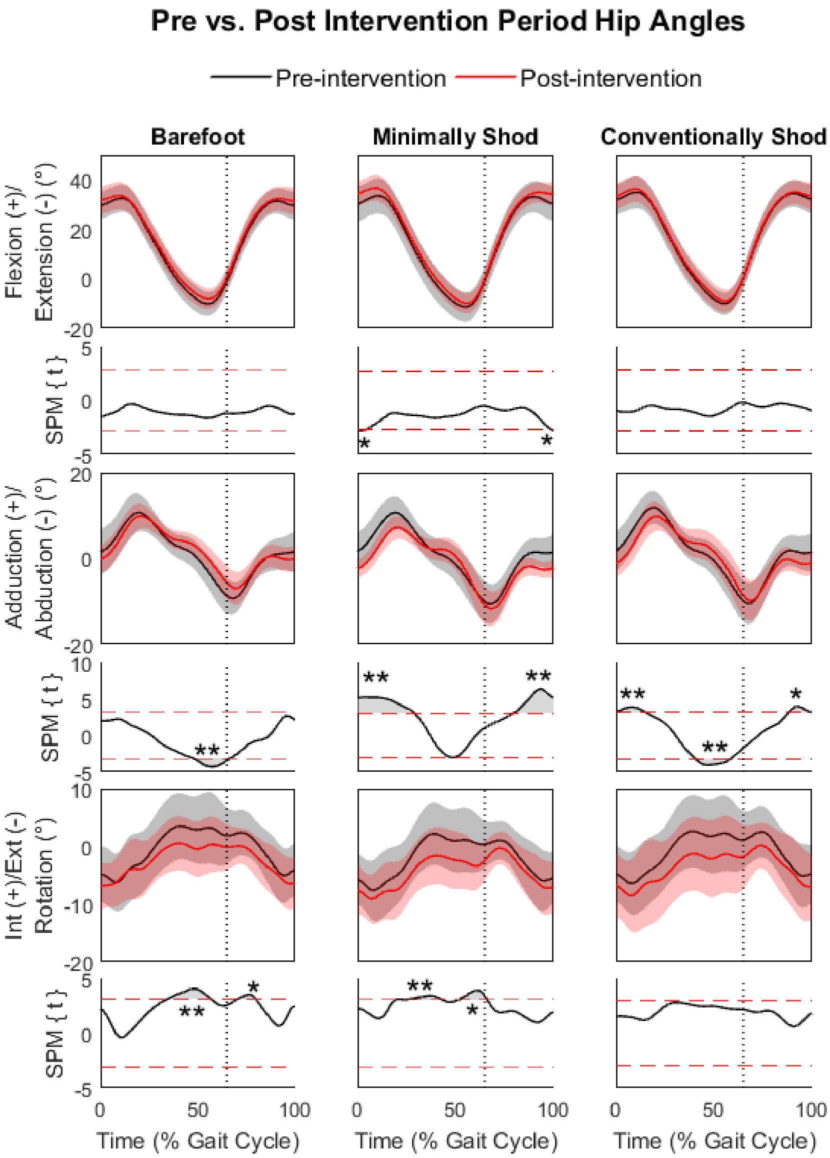

Figure 7.20: Intervention participants' pre and post intervention period hip angles in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

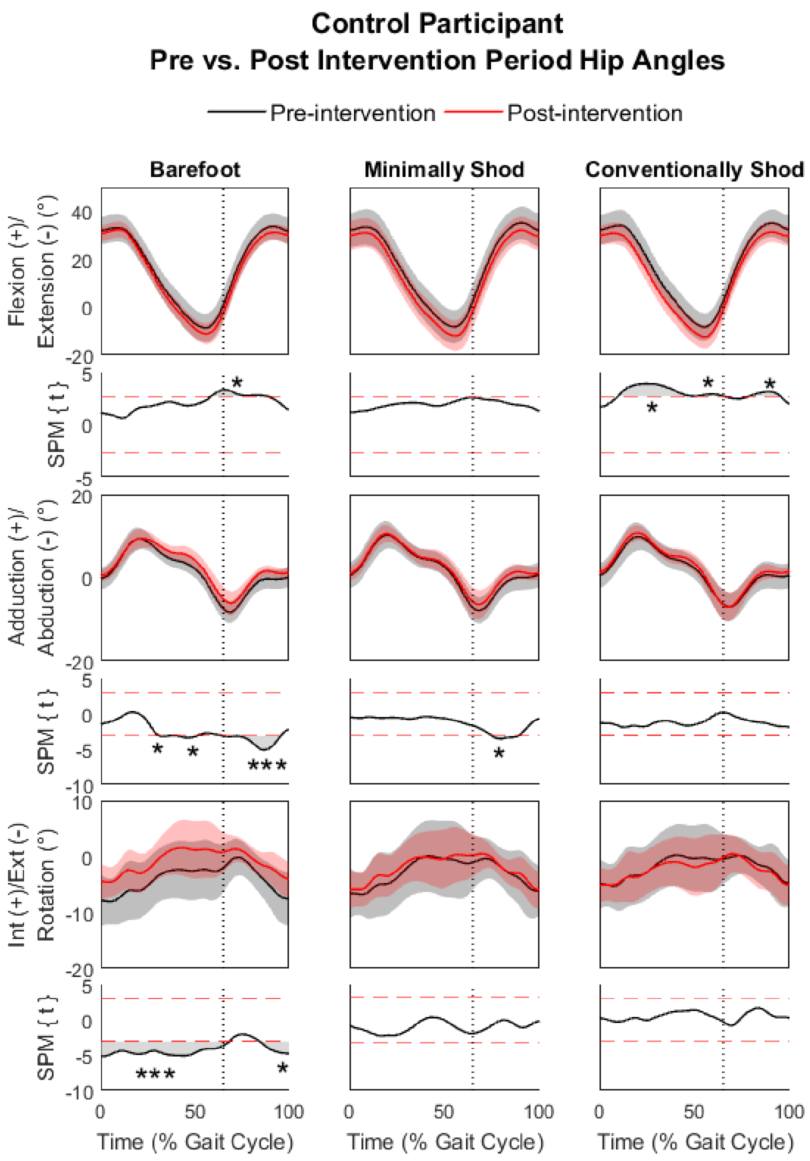

Figure 7.21: Control participants' pre and post intervention period hip angles in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=23), minimally shod (M; n=22) and conventionally shod (C; n=23). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

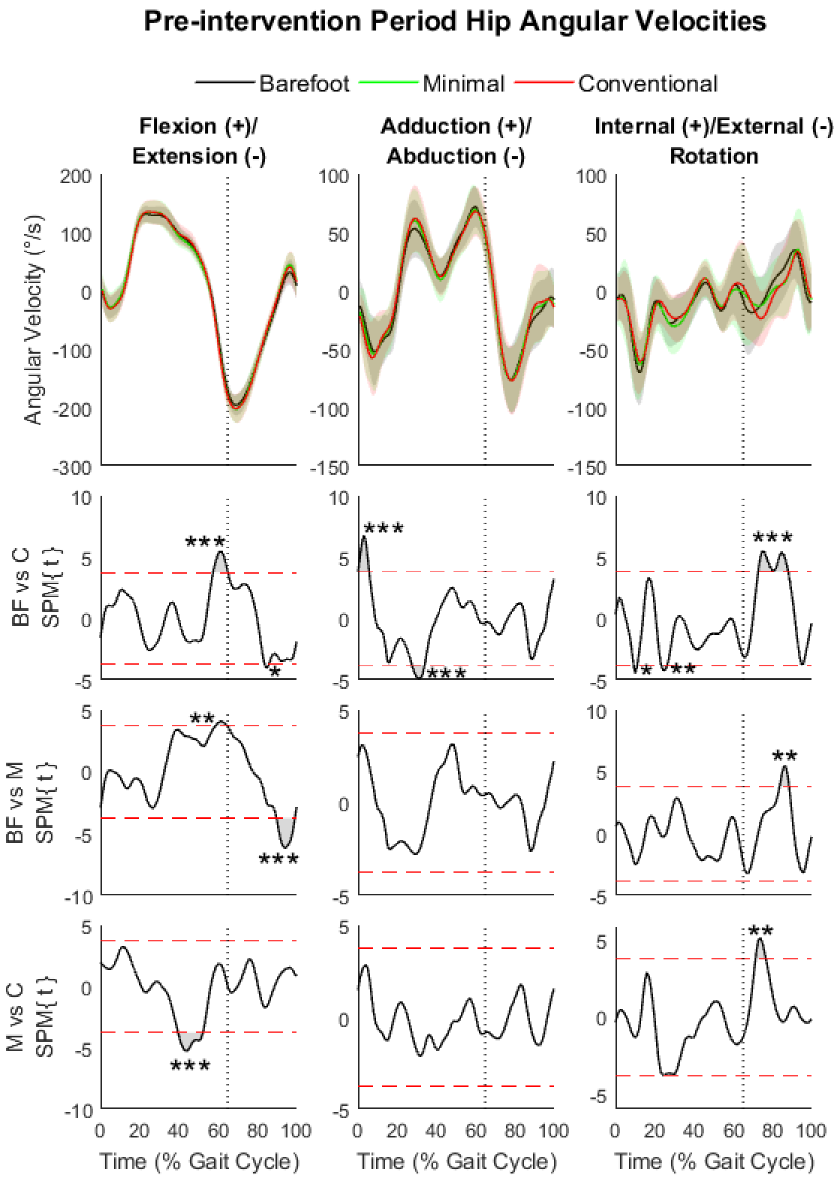

Figure 7.22: Pre-intervention participants' hip angular velocities in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=50) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

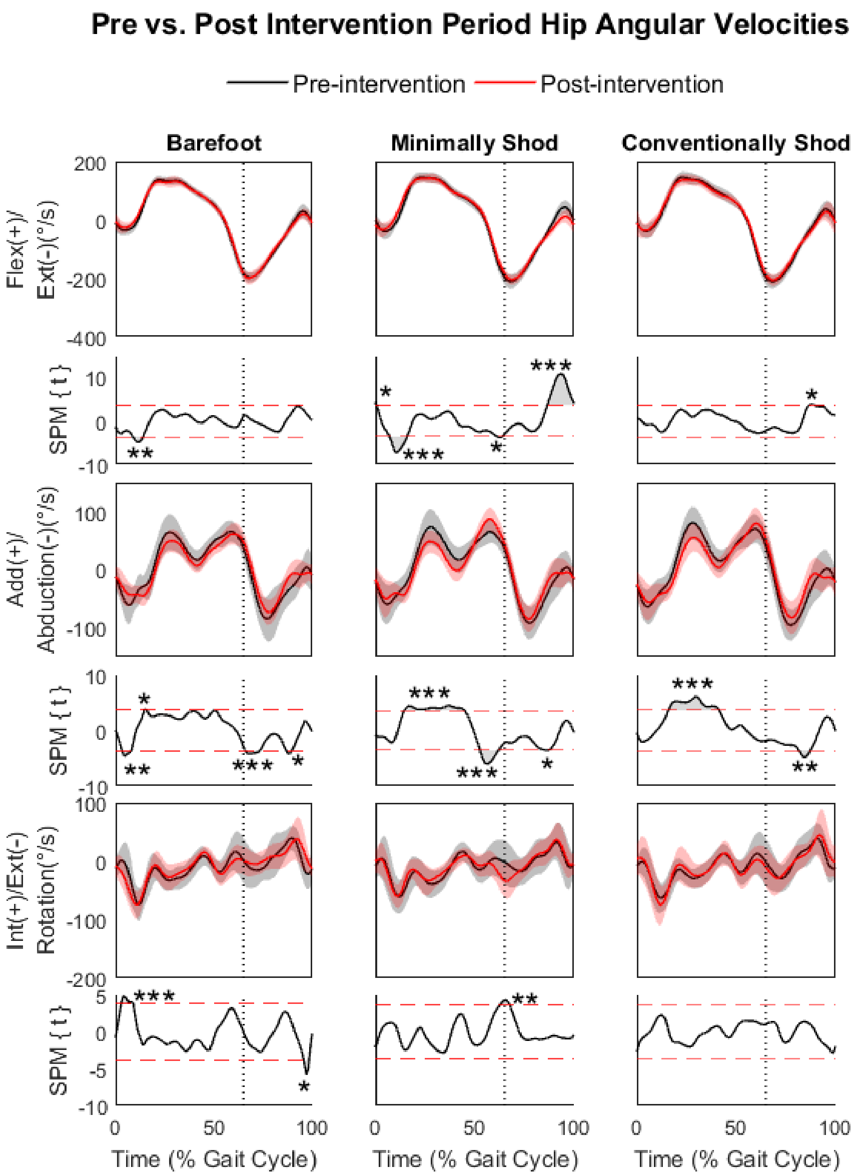

Figure 7.23: Intervention participants' pre and post intervention period hip angular velocities in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

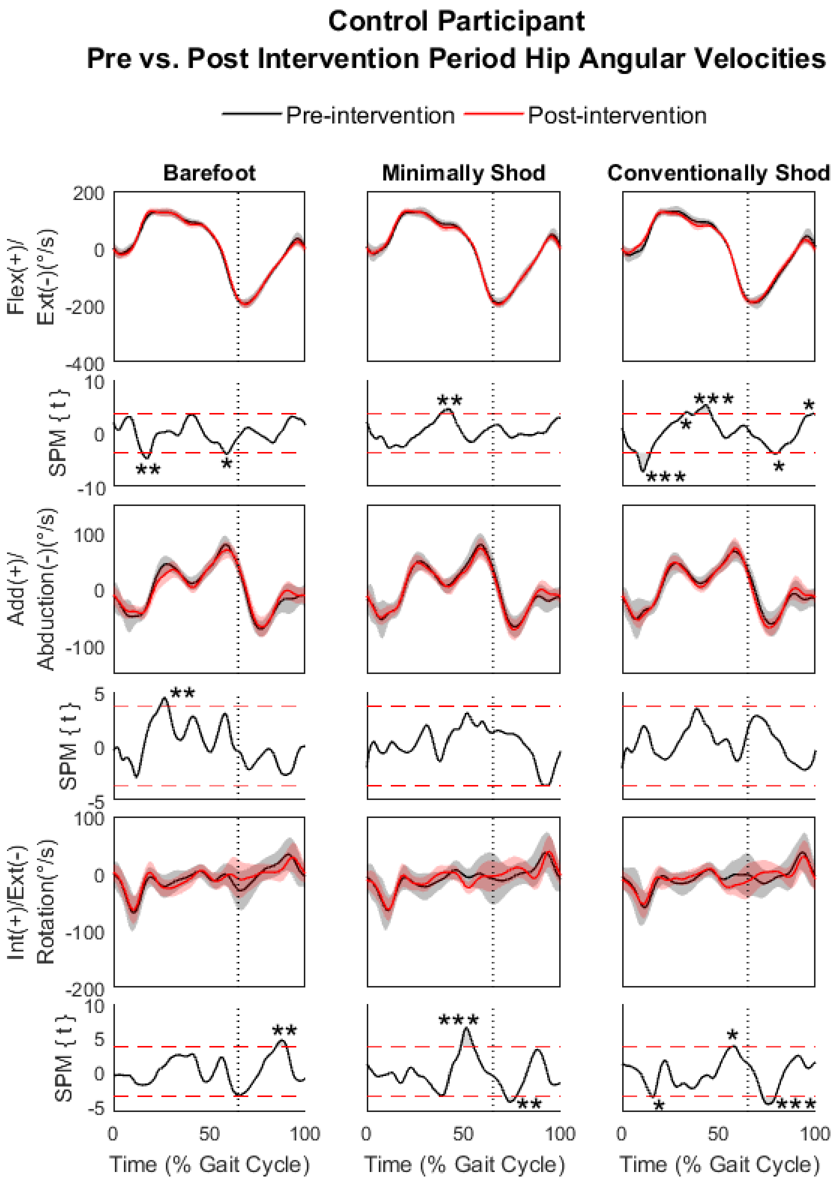

Figure 7.24: Control participants' pre and post intervention period hip angular velocities in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=23), minimally shod (M; n=22) and conventionally shod (C; n=23). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

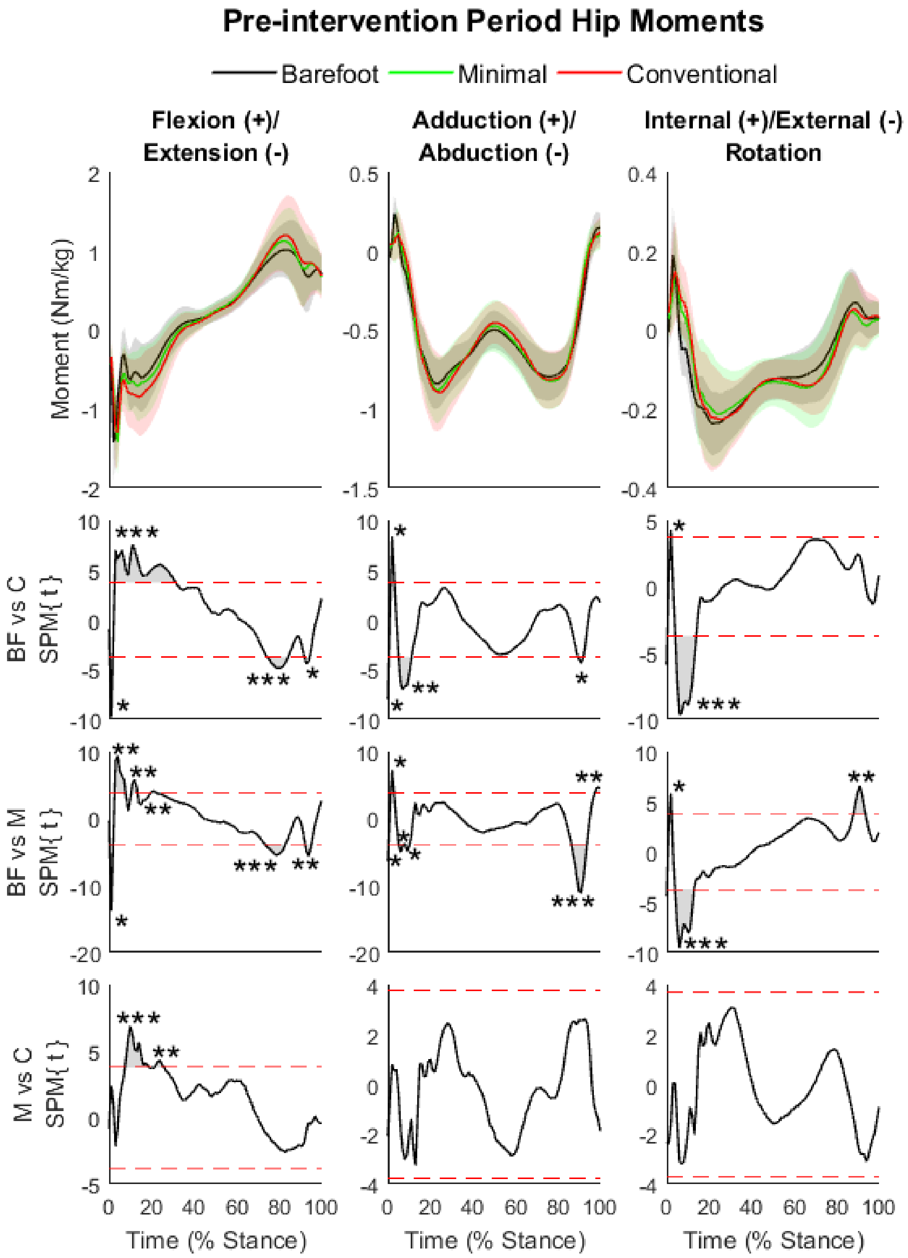

Figure 7.25: Pre-intervention participants' hip moments in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=40) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

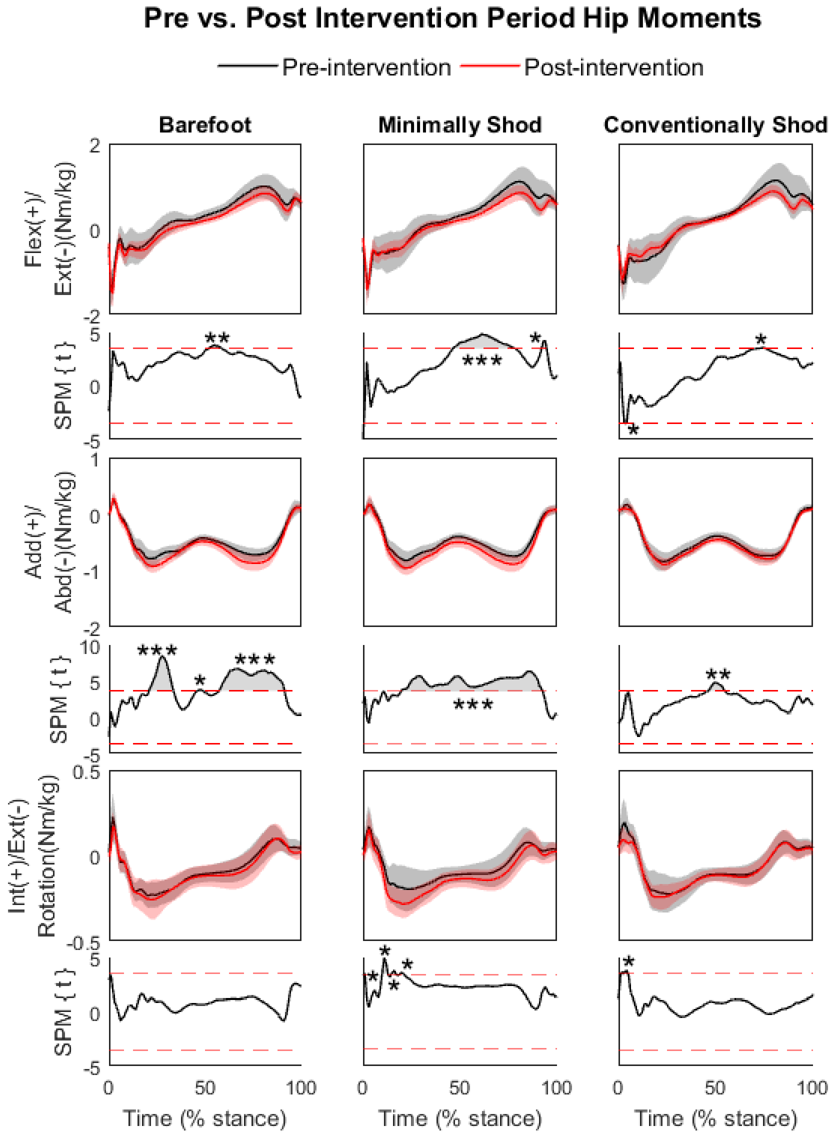

Figure 7.26: Intervention participants' pre and post intervention period hip moments in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=21) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

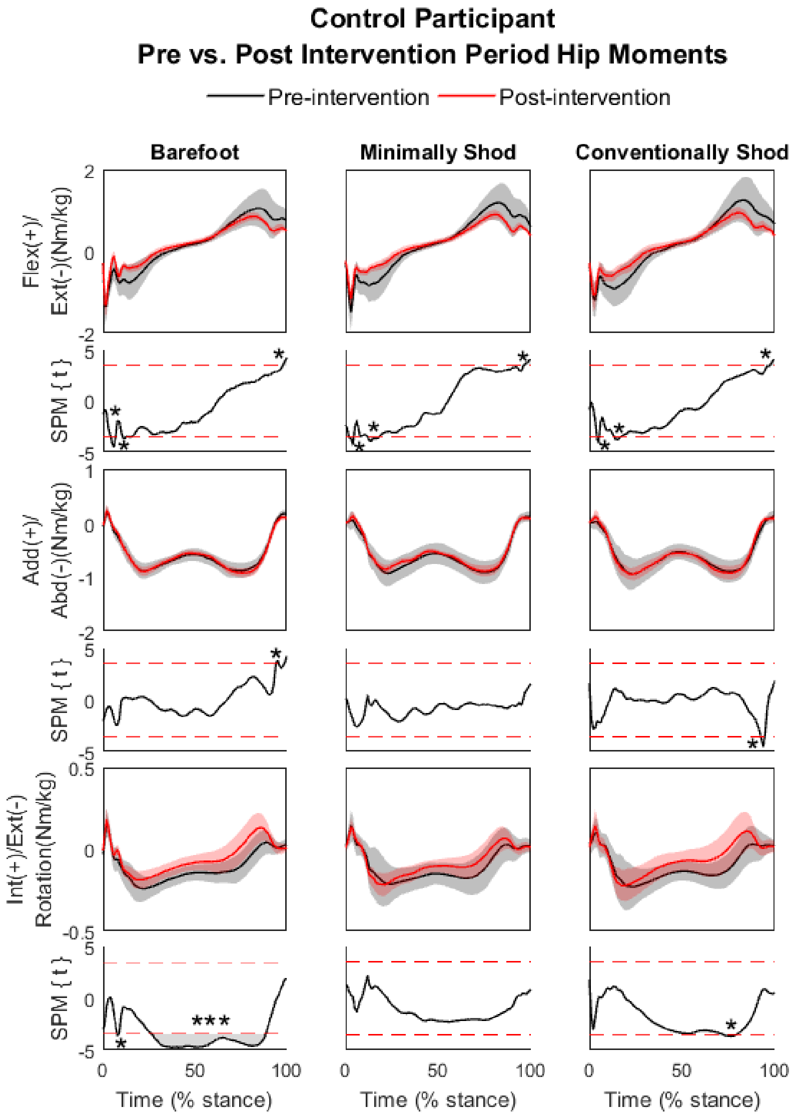

Figure 7.27: Control participants' pre and post intervention period hip moments in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=19), minimally shod (M; n=18) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

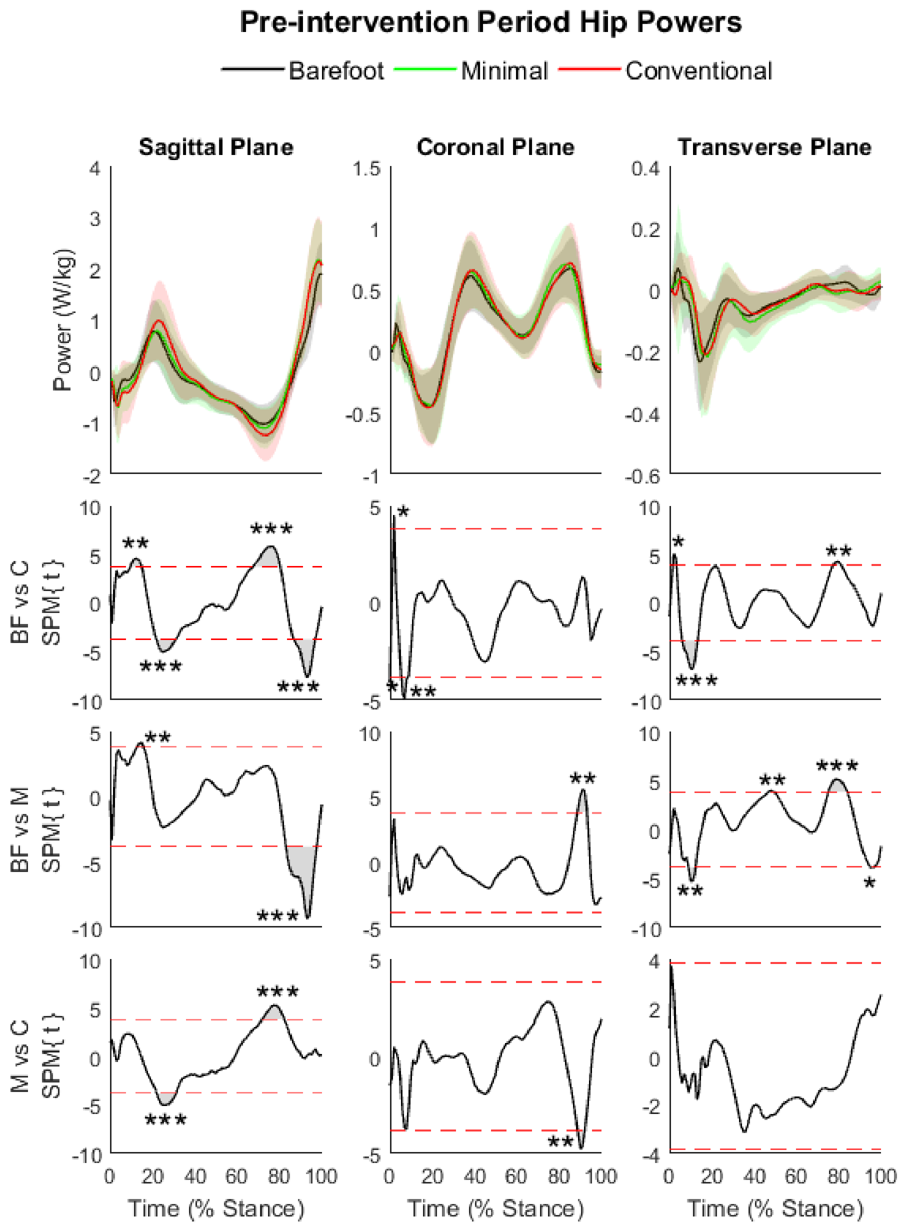

Figure 7.28: Pre-intervention participants' hip powers in the Sagittal (X), Coronal (Y) and Transverse (Z) planes (n=41) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

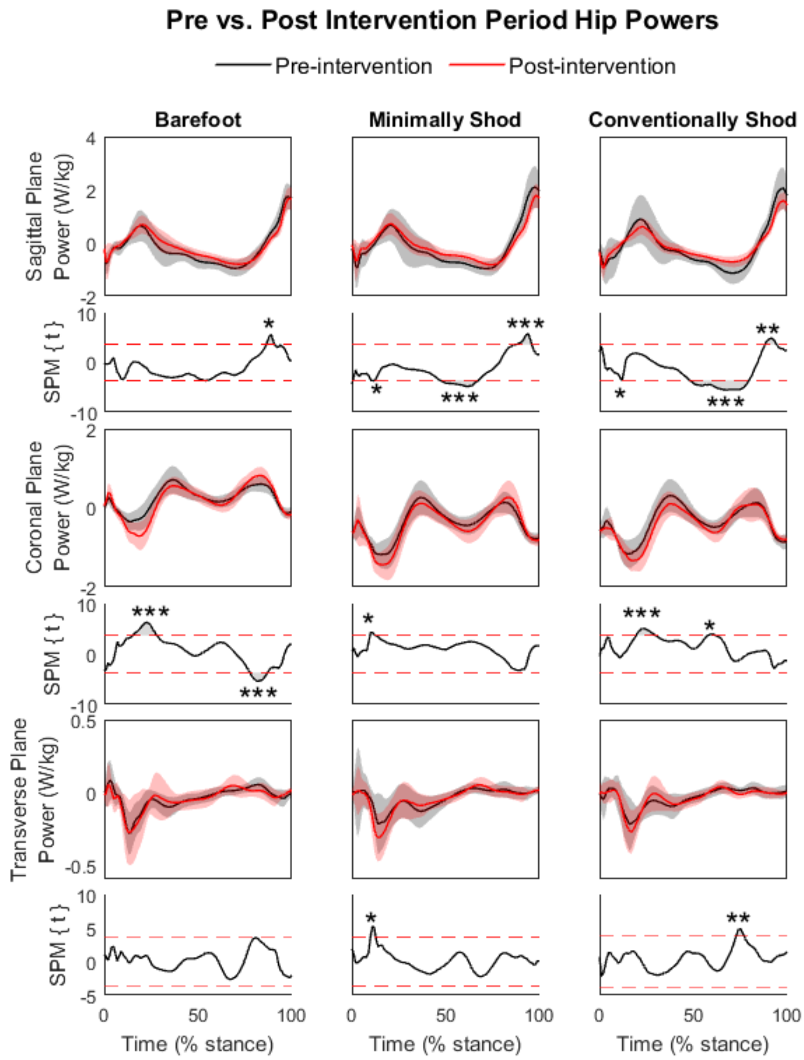

Figure 7.29: Intervention participants' pre and post intervention period hip powers in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=21), minimally shod (M; n=21) and conventionally shod (C; n=20). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

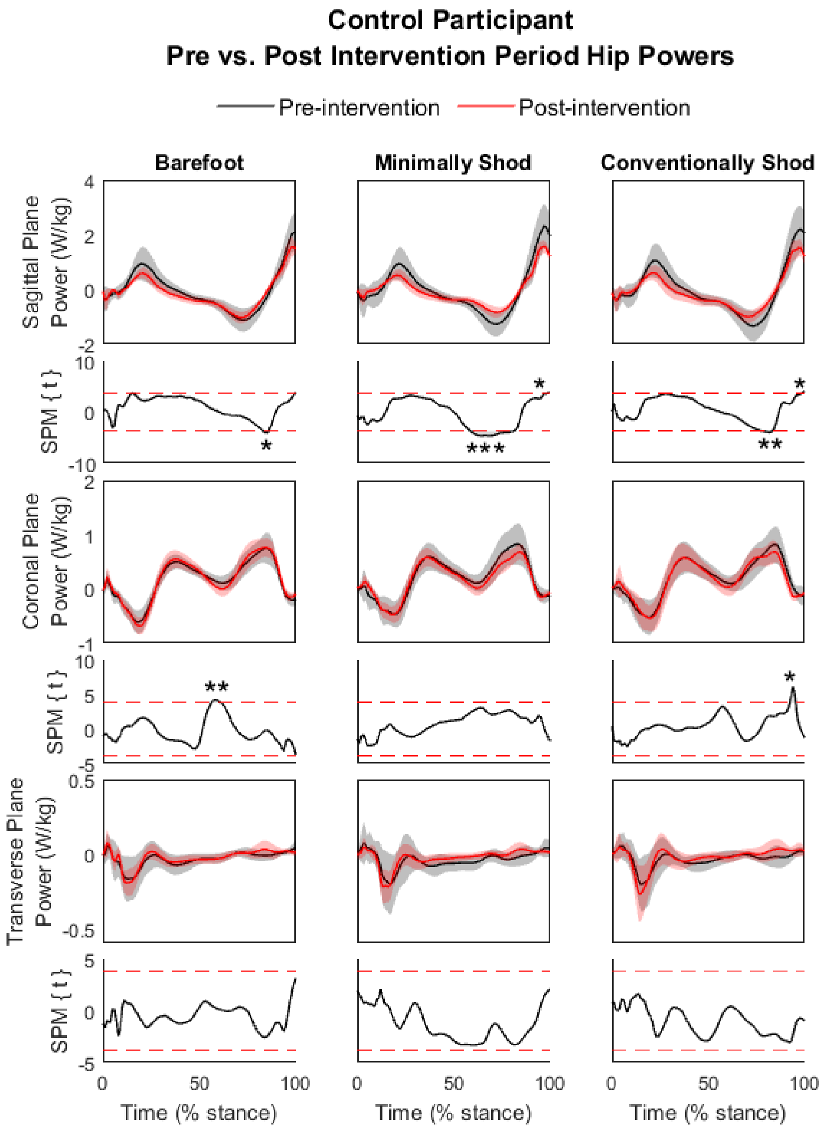

Figure 7.30: Control participants' pre and post intervention period hip powers in the sagittal (X), coronal (Y) and transverse (Z) planes while walking barefoot (BF; n=19), minimally shod (M; n=18) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

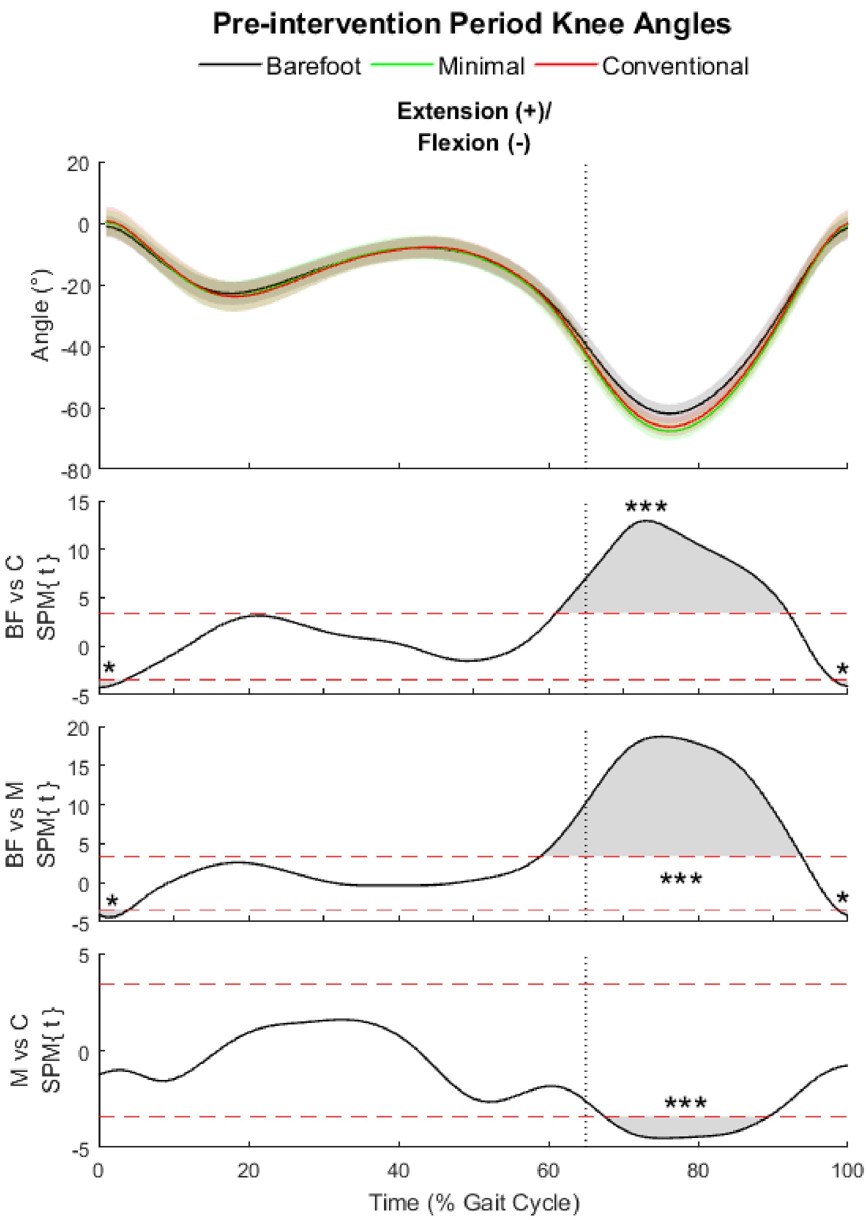

Figure 7.31: Pre-intervention participants' knee angles in the Sagittal (X) plane (n=50) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

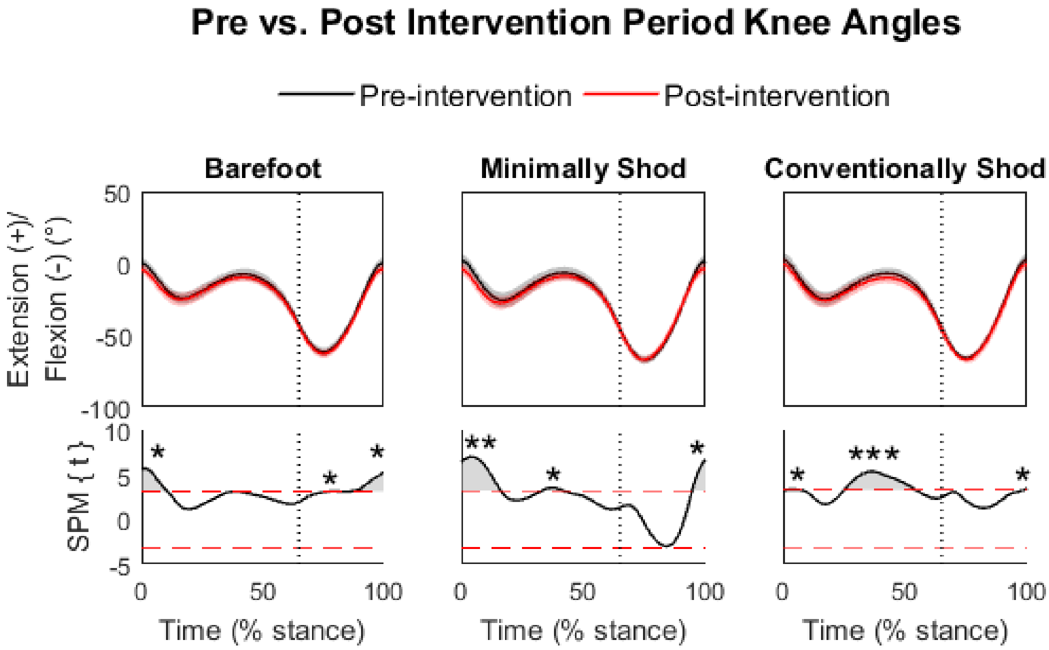

Figure 7.32: Intervention participants' pre and post intervention period hip angles in the sagittal (X) plane while walking barefoot (BF; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

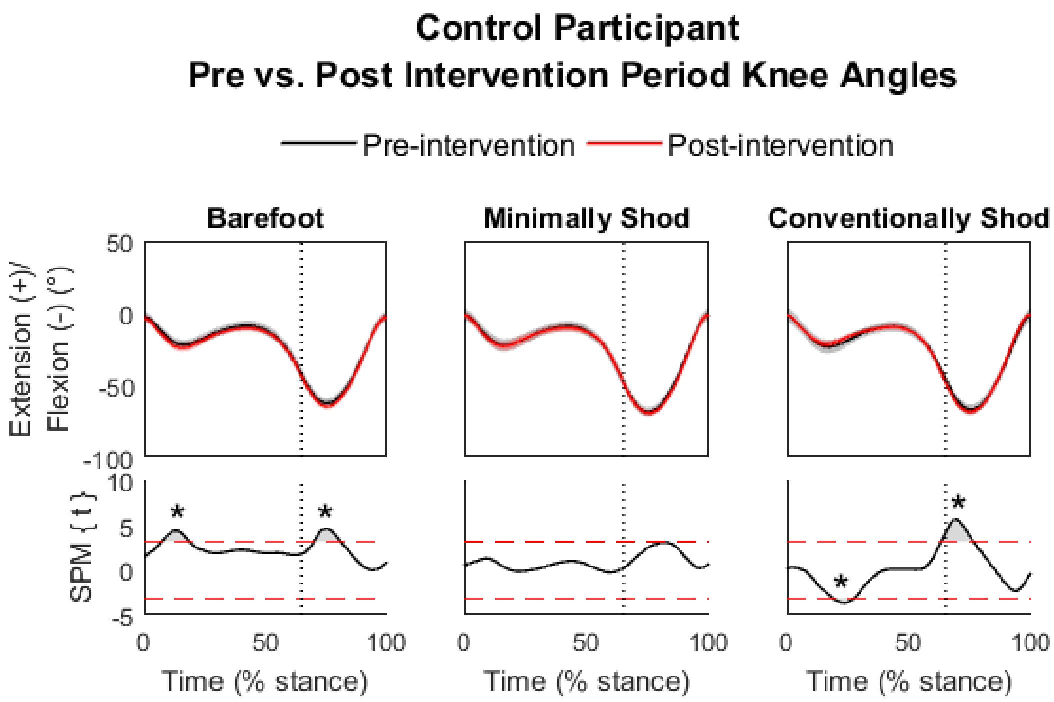

Figure 7.33: Control participants' pre and post intervention period hip angles in the sagittal (X) plane while walking barefoot (BF; n=23), minimally shod (M; n=22) and conventionally shod (C; n=23). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

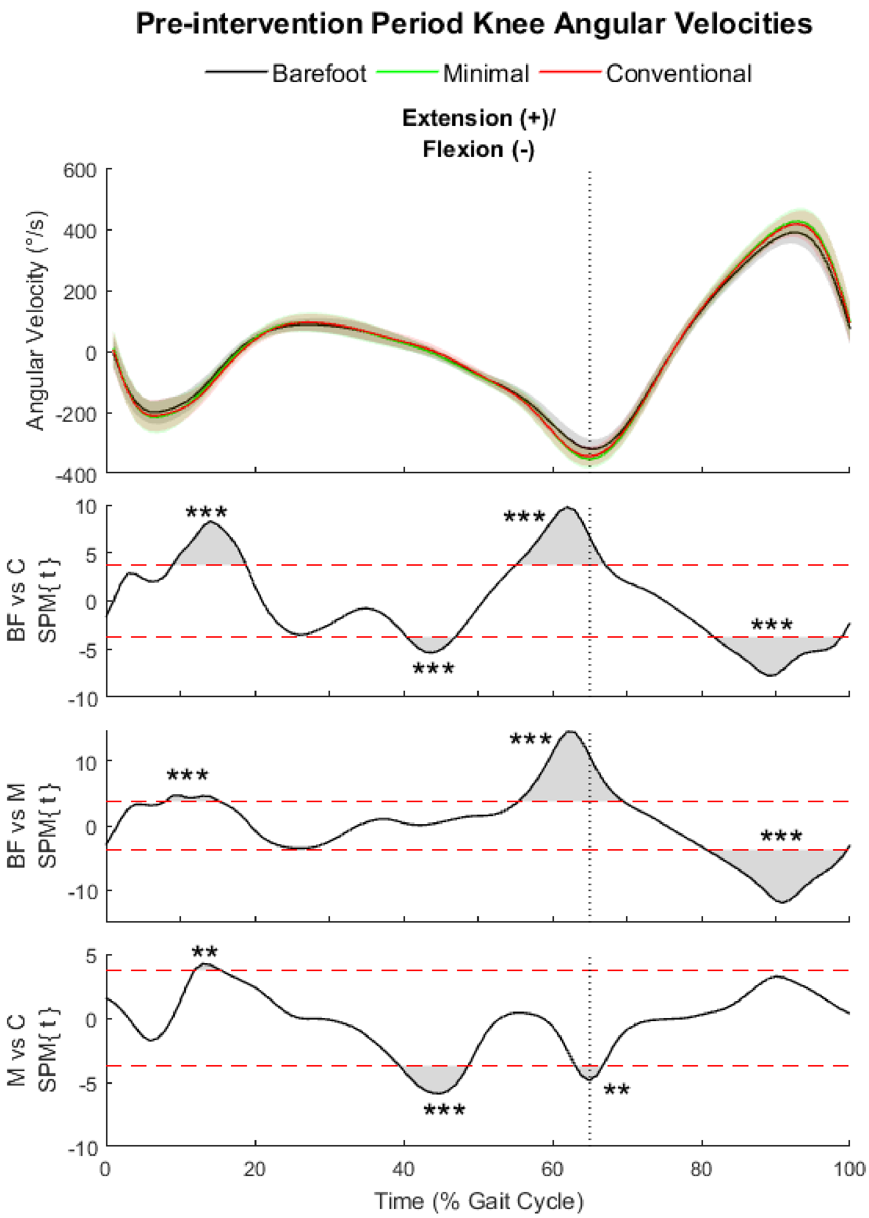

Figure 7.34: Pre-intervention participants' knee angular velocities in the Sagittal (X) plane (n=50) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

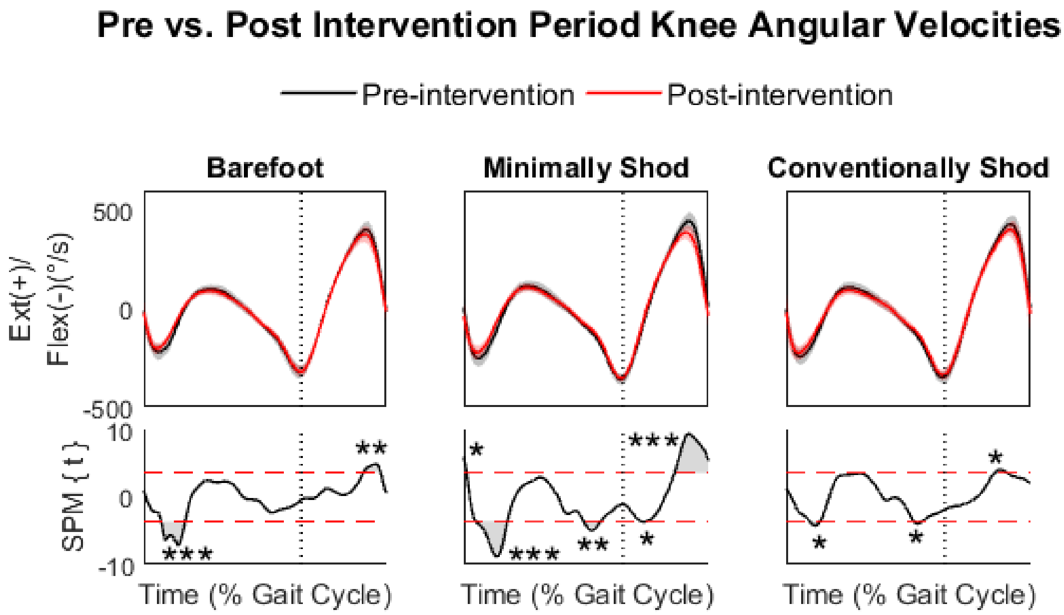

Figure 7.35: Intervention participants' pre and post intervention period hip angular velocities in the sagittal (X) plane while walking barefoot (BF; n=21), minimally shod (M; n=22) and conventionally shod (C; n=21). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

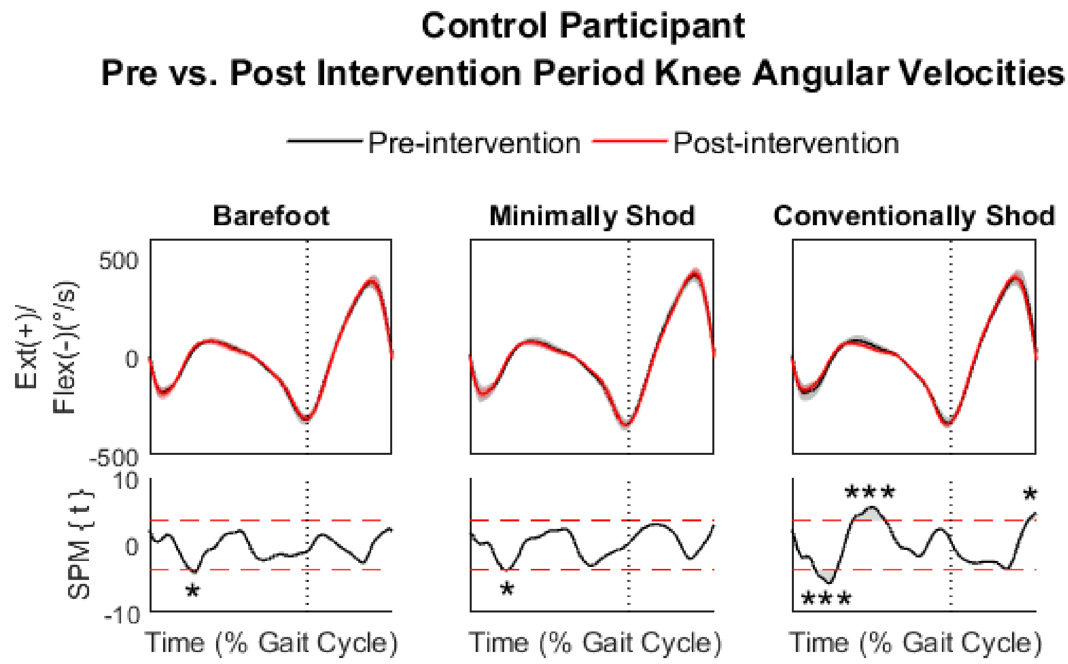

Figure 7.36: Control participants' pre and post intervention period hip angular velocities in the sagittal (X) plane while walking barefoot (BF; n=23), minimally shod (M; n=22) and conventionally shod (C; n=23). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

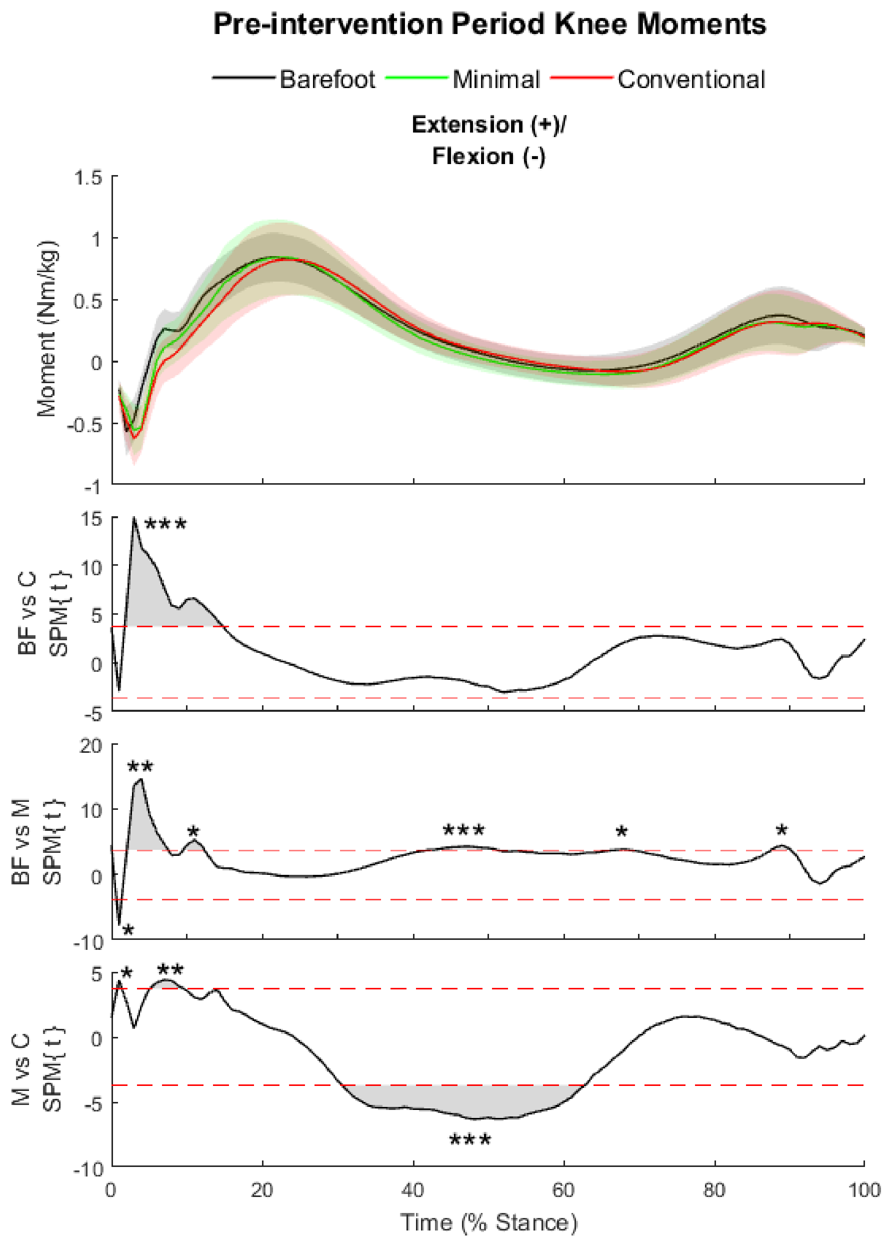

Figure 7.37: Pre-intervention participants' knee moments in the Sagittal (X) plane (n=40) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

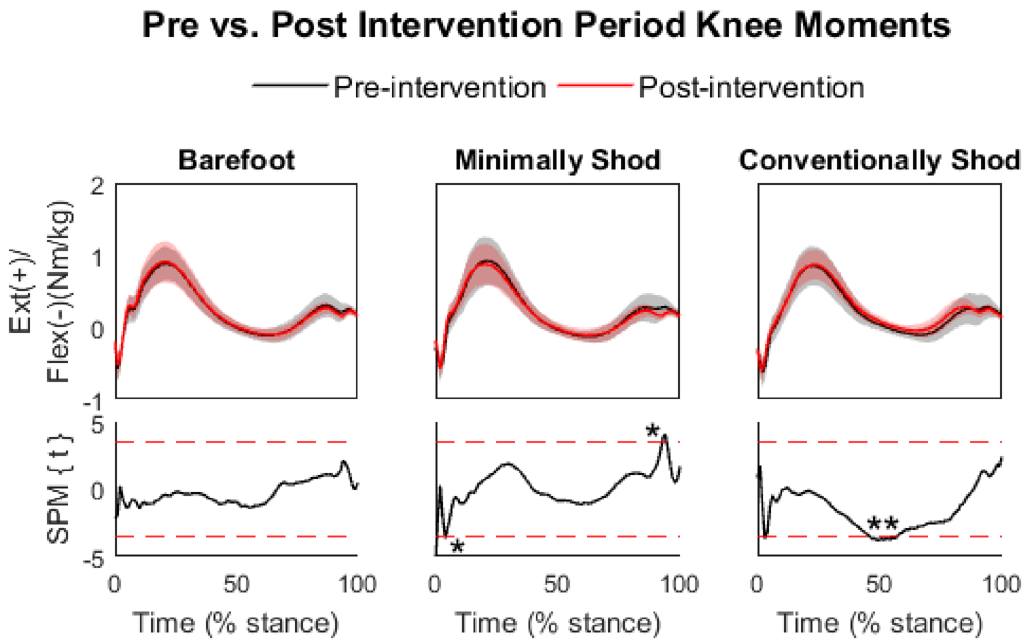

Figure 7.38: Intervention participants' pre and post intervention period hip moments in the sagittal (X) plane while walking barefoot (BF; n=21), minimally shod (M; n=21) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

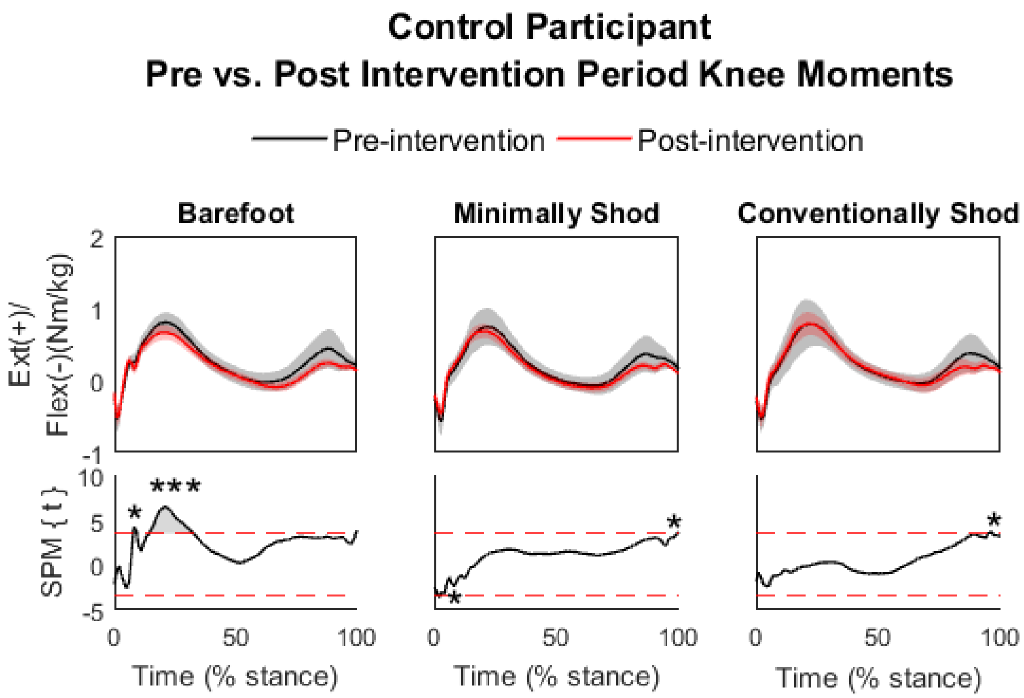

Figure 7.39: Control participants' pre and post intervention period hip moments in the sagittal (X) plane while walking barefoot (BF; n=19), minimally shod (M; n=18) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

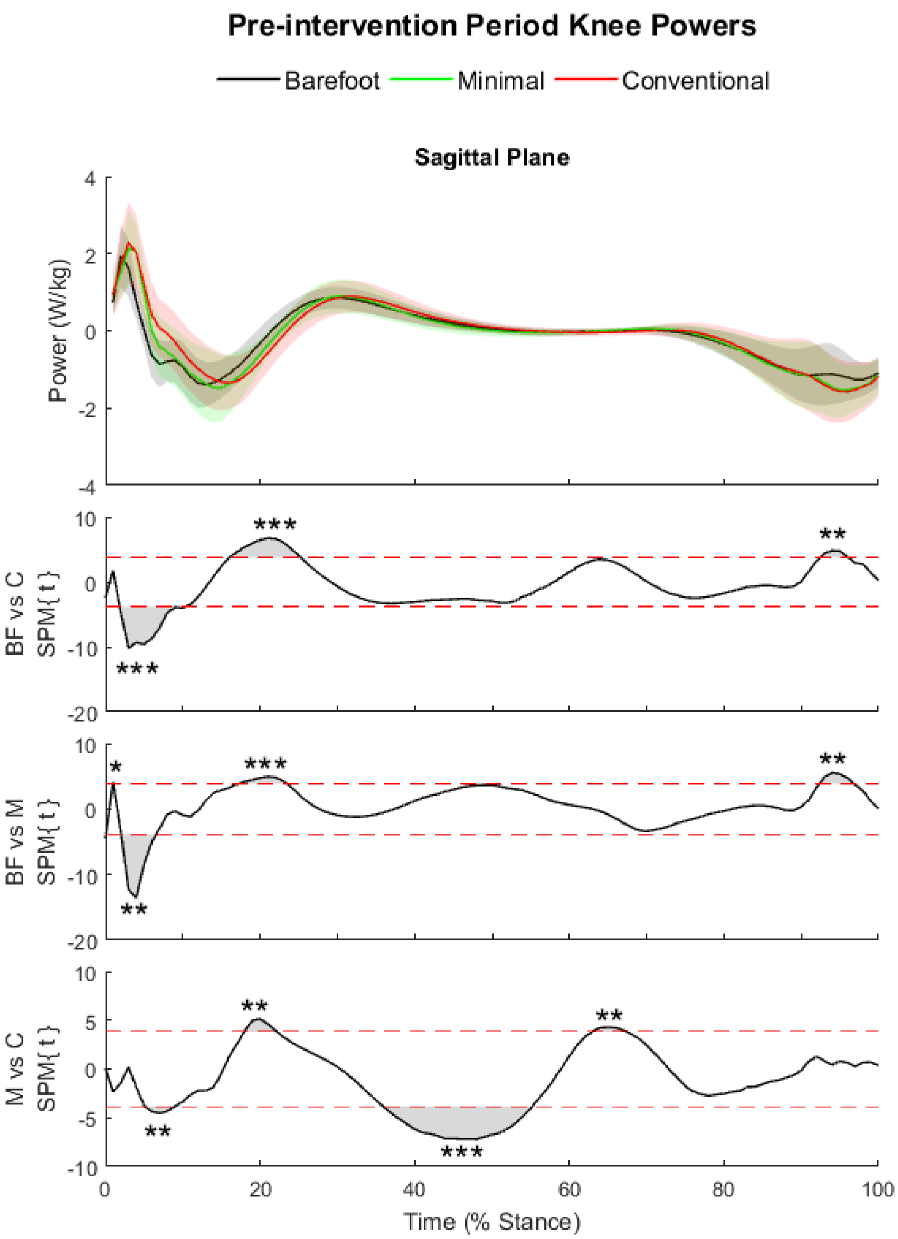

Figure 7.40: Pre-intervention participants' knee powers in the Sagittal (X) plane (n=41) while walking barefoot (BF), minimally shod (M) and conventionally shod (C). The vertical dotted lines indicate toe-off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests with Bonferroni corrections) indicate regions of statistically significant differences between walking conditions, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

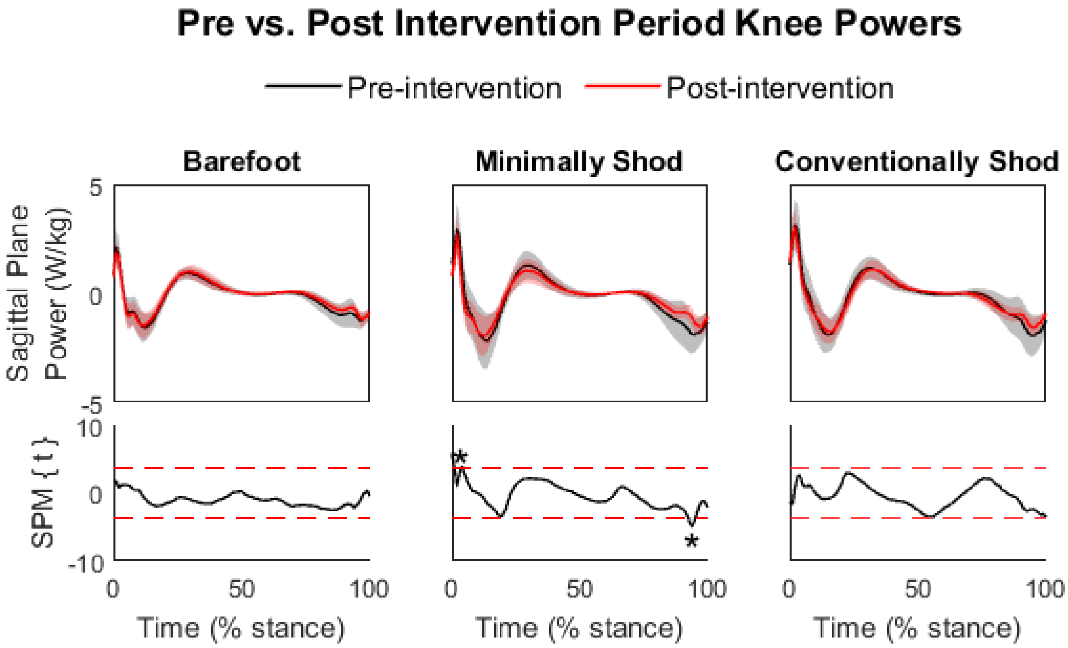

Figure 7.41: Intervention participants' pre and post intervention period hip powers in the sagittal (X) plane while walking barefoot (BF; n=21), minimally shod (M; n=21) and conventionally shod (C; n=20). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*

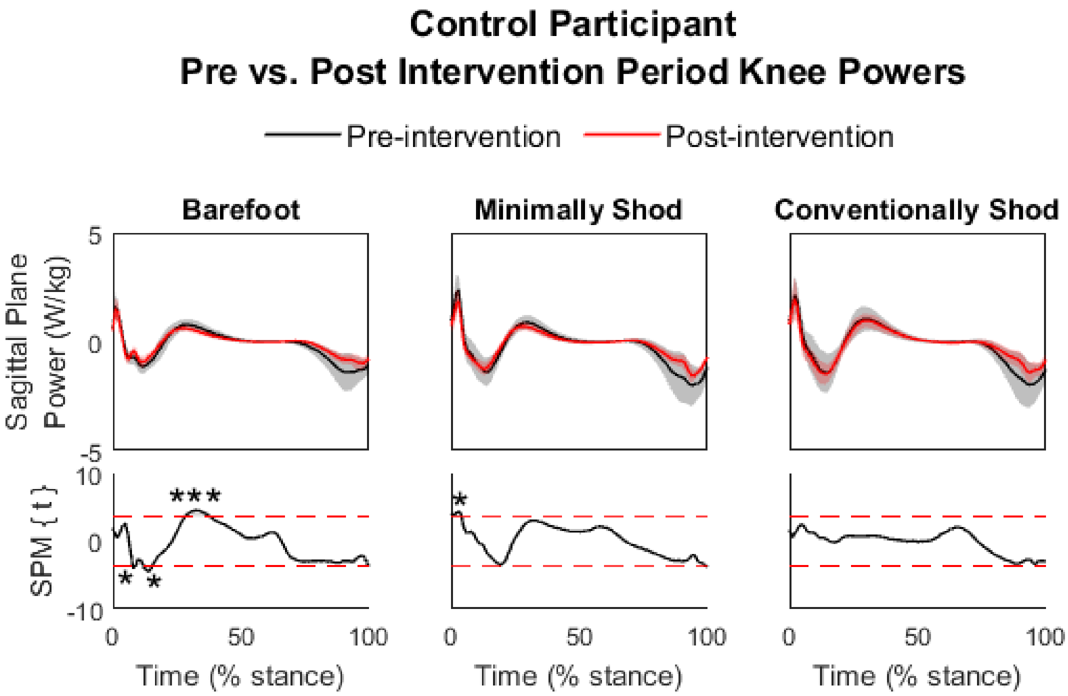

Figure 7.42: Control participants' pre and post intervention period hip powers in the sagittal (X) plane while walking barefoot (BF; n=19), minimally shod (M; n=18) and conventionally shod (C; n=19). The vertical dotted lines indicate toe off. One dimensional statistical parametric mapping – 1D-SPM (utilising paired t-tests) indicate regions of statistically significant differences between walking conditions pre and post intervention period, when 1D-SPM lines exceed the critical threshold values denoted by the horizontal red dotted lines. Shaded regions (within the SPM graphs) correspond to the period within the gait cycle where walking conditions pre and post intervention period are statistically significantly different from one another. ", **, ***" represent p-values of less than 0.05, 0.01 and 0.001 respectively.*